IsoDAR and Neutrino-Electron Scattering Experiments

Workshop on the Intermediate Neutrino Program

M. Toups

2/5/15

Outline

- The Isotope Decay-At-Rest Experiment (IsoDAR)
- IsoDAR Challenges
- $\bar{\nu}_e e \ (\nu_e e)$ scattering experiments

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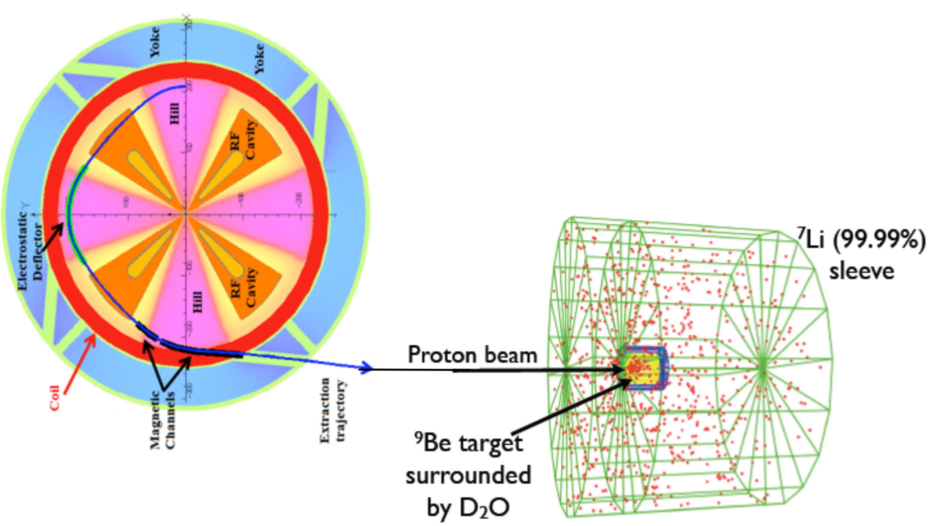
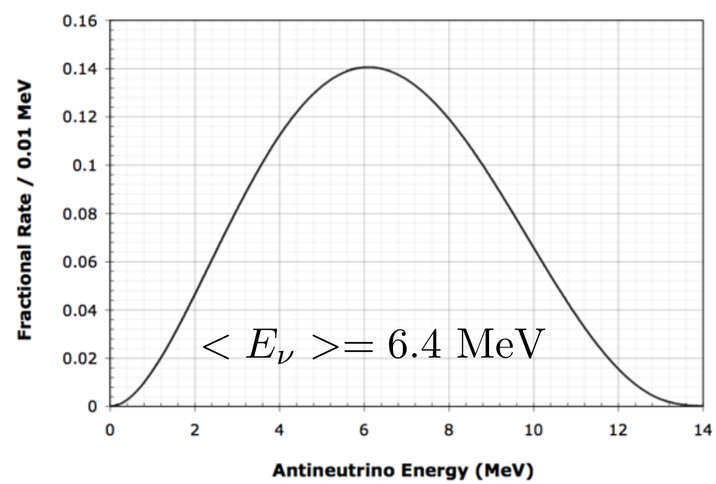
The IsoDAR $\bar{\nu}_e$ Source

Proton beam → Be → n → captures on ^{7}Li → ^{8}Li → $\bar{\nu}_e$



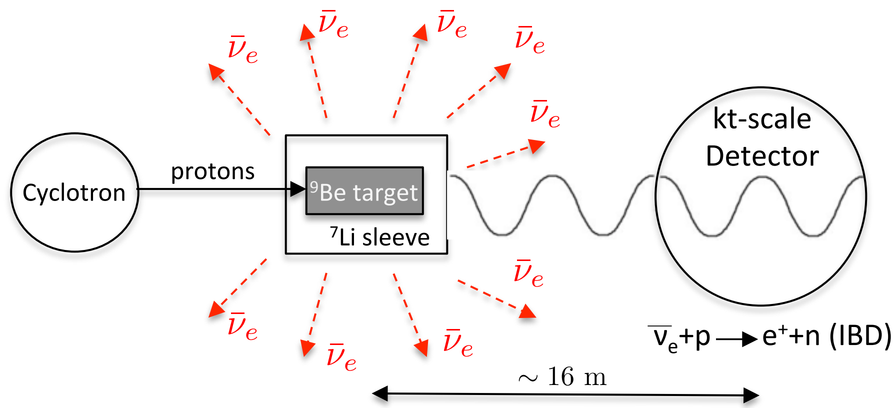


$5\ \mathrm{mA}\ H_2^+\ @\ 60\ \mathrm{MeV}/n$
(600 kW proton beam)

$^8\mathrm{Li} \rightarrow ^8\mathrm{Be} + e^- + \bar{\nu}_e$

Produces $1.29 \times 10^{23}\ \bar{\nu}_e$ in 5 years (with 90% duty factor)

The IsoDAR Experiment

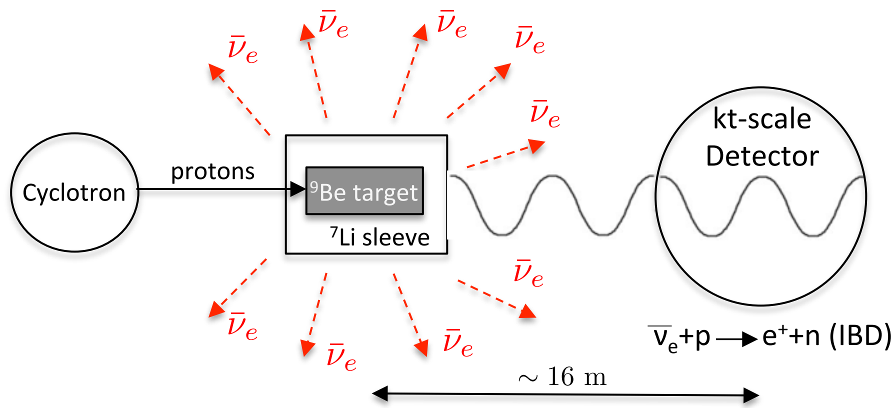


$$1/L^2 \text{ flux rate modulated by } \mathrm{Prob}_{osc} = \sin^2 2\theta \cdot \sin^2\left(\Delta m^2 L/4E\right)$$

Key features of IsoDAR setup:

- High statistics
- Compact antineutrino source
  - Bring source to underground detector
  - $\sigma_x = \sigma_y = 23$ cm and $\sigma_z = 37$ cm (see backup)
- Well understood energy spectrum
  - ^{8}Li β-decay dominates $\bar{\nu}_e$ flux (see backup)
  - Above 3 MeV environmental backgrounds
- Pair with kton-scale underground IBD detector
  - Both L and E accurately reconstructed
  - Delayed coincidence signal reduces backgrounds
  - Backgrounds don't show L/E oscillation behavior

The IsoDAR Experiment



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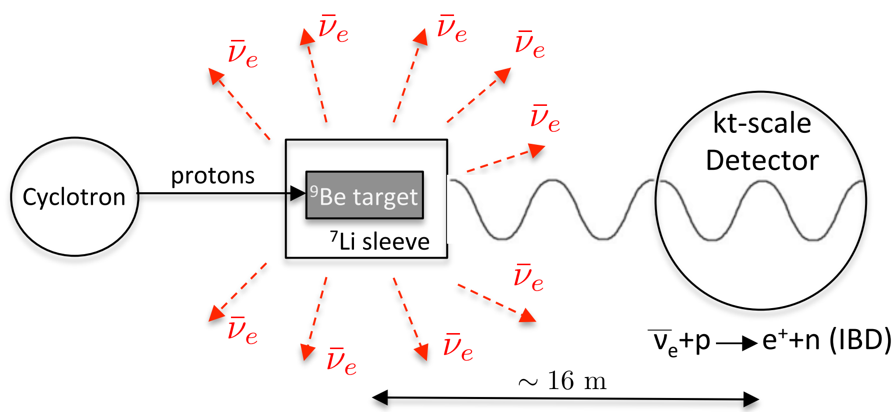
Negligible backgrounds

The IsoDAR Experiment



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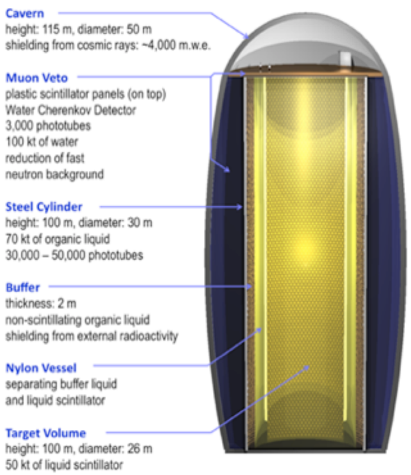
Negligible backgrounds

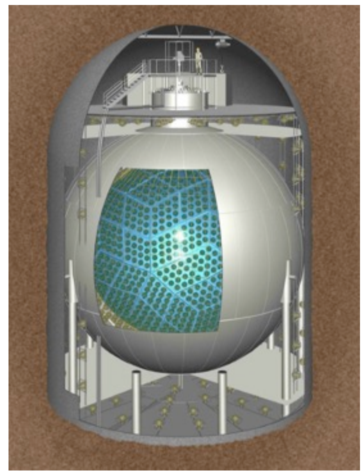
Good control of systematics

Where Can IsoDAR Run?

LENA

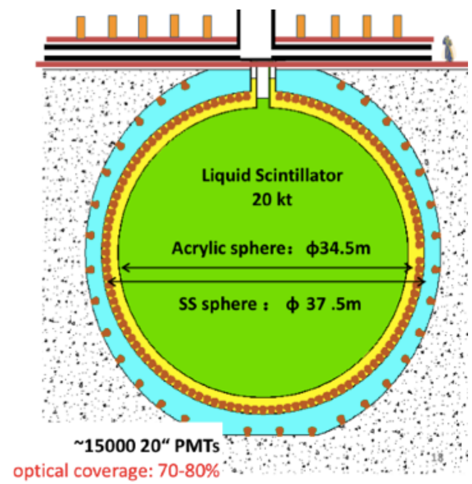


KamLAND

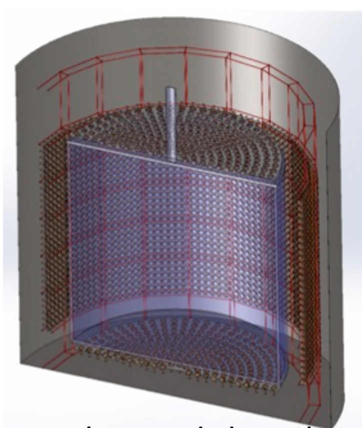


1 kton liquid scintillator

JUNO

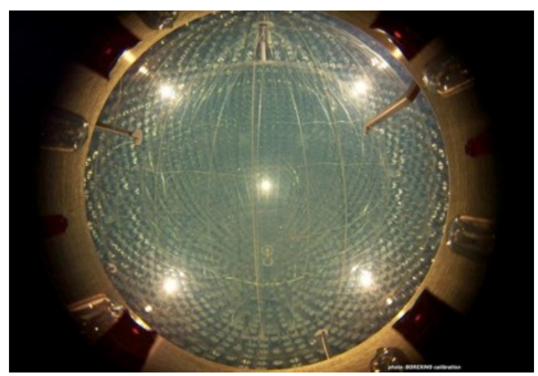


WATCHMAN

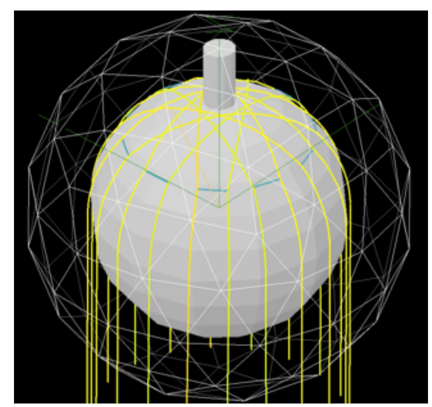


1 kton Gd-doped
water Cerenkov

Borexino



SNO+



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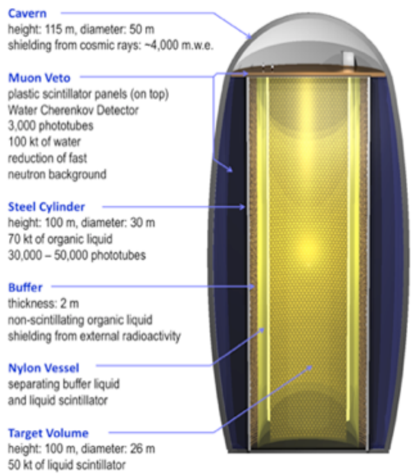

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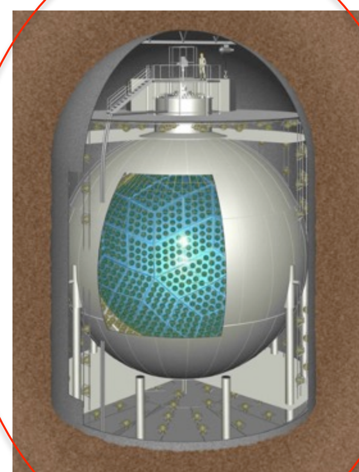

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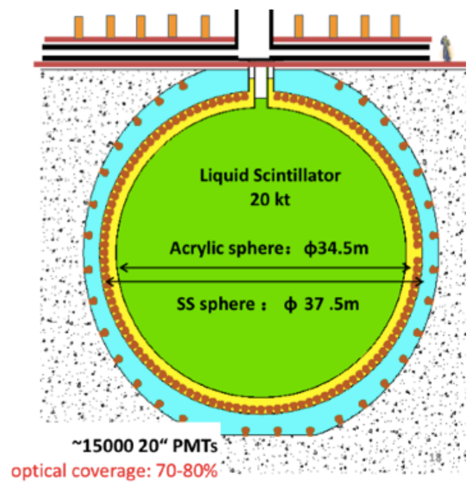

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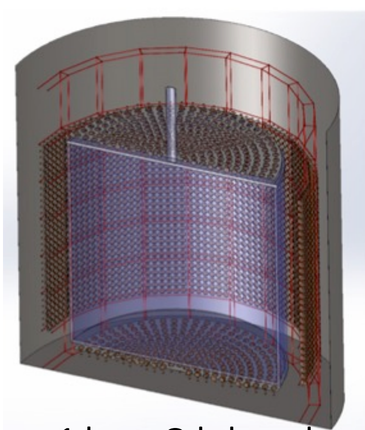

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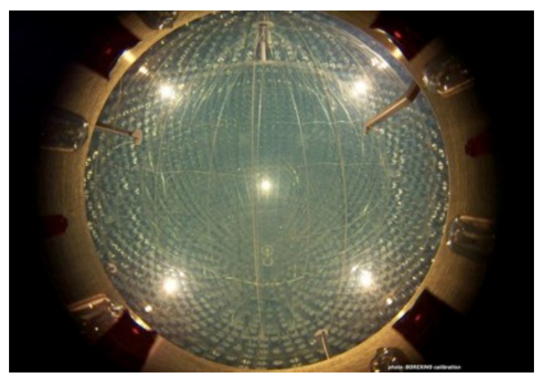

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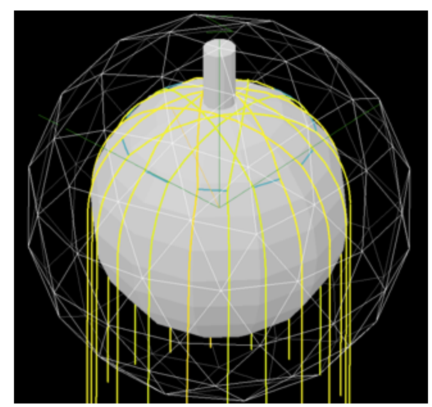
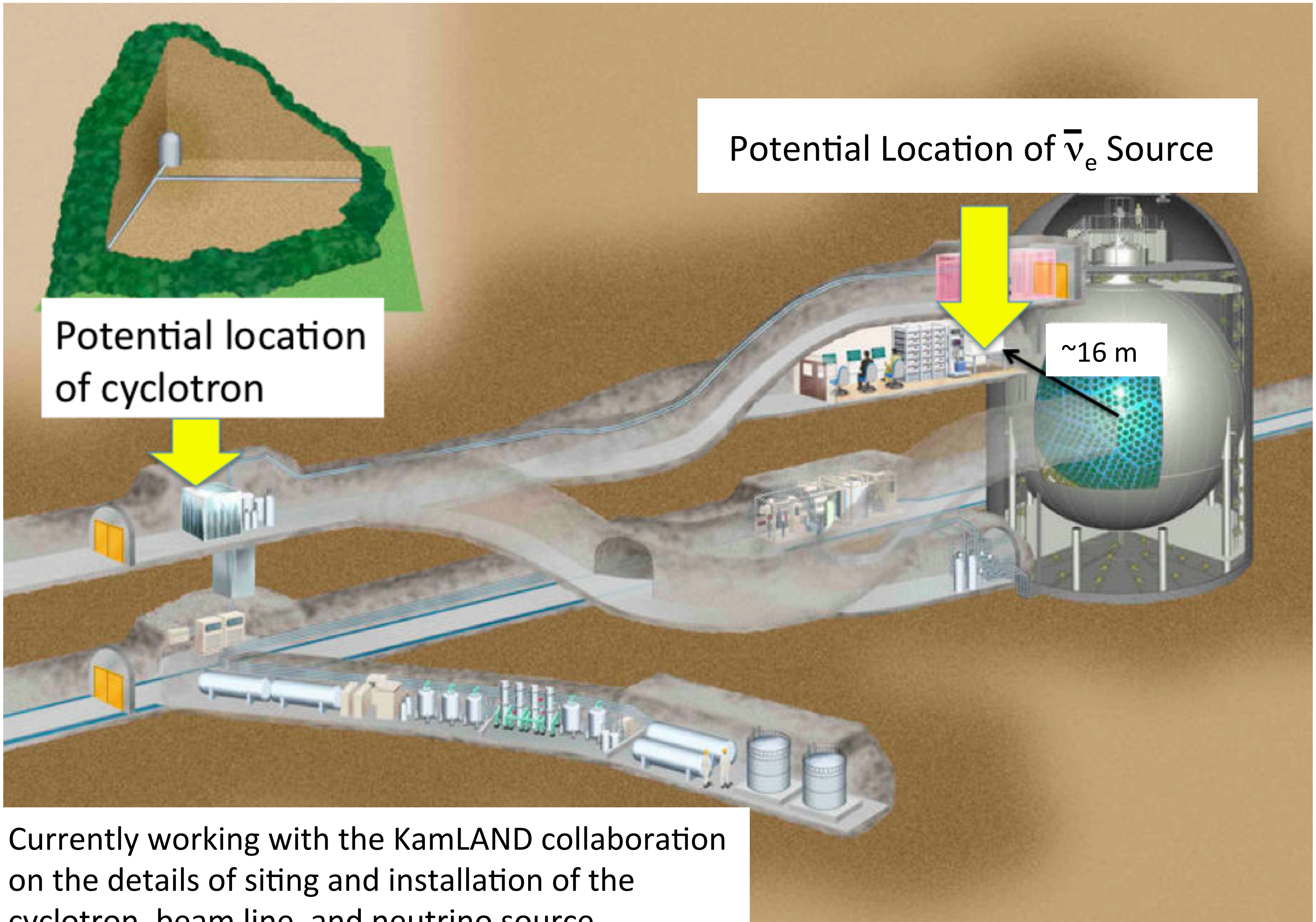
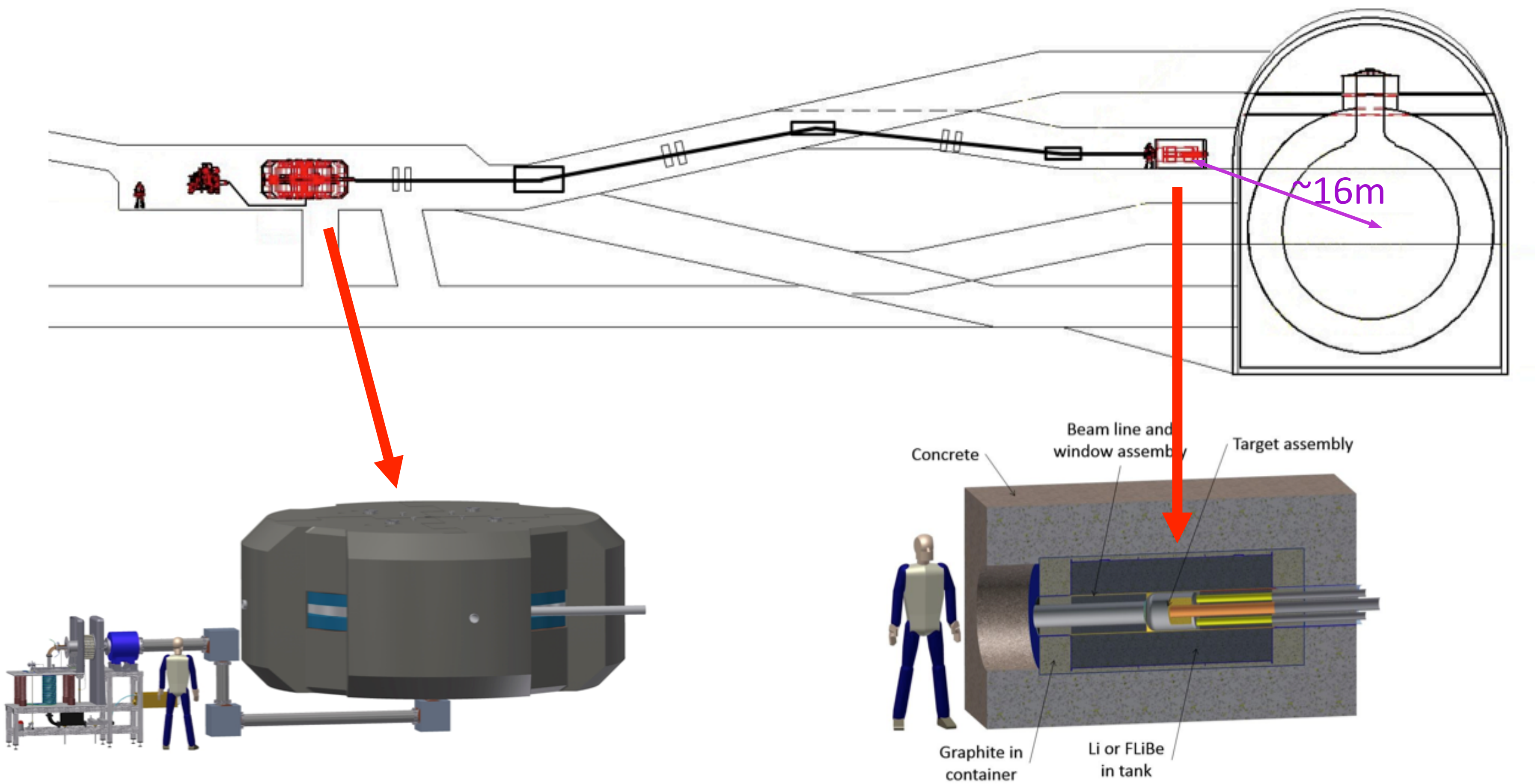


IsoDAR at KamLAND



Currently working with the KamLAND collaboration on the details of siting and installation of the cyclotron, beam line, and neutrino source.

Cyclotron and Isotope Antineutrino Source Installed at KamLAND

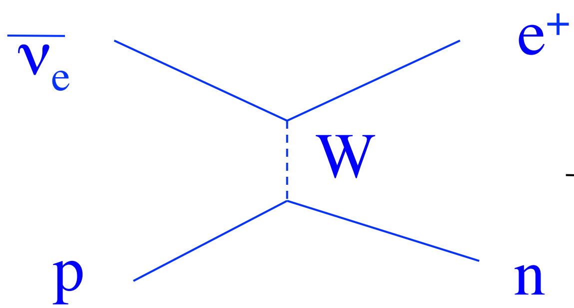


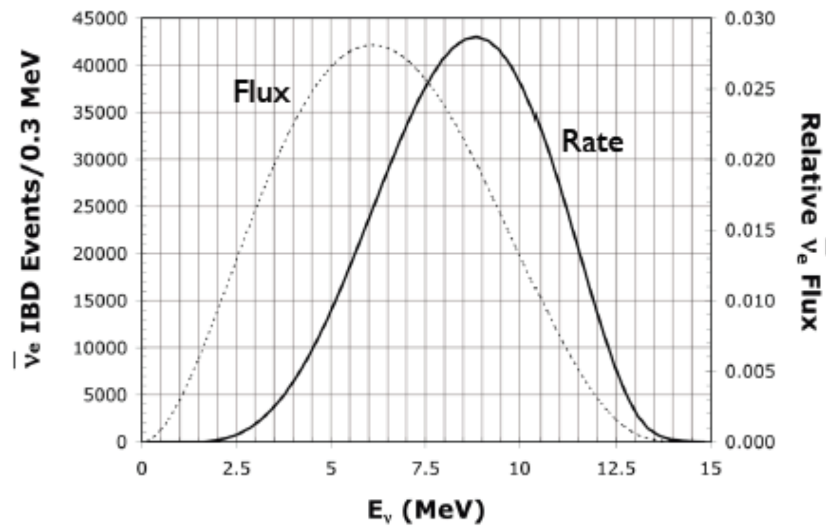
60 MeV/n 5 mA H_2^+ Cyclotron

^{9}Be/^{7}Li Target and $\bar{\nu}_e$ Source

Five Years of Running at KamLAND

Inverse β Decay (IBD)



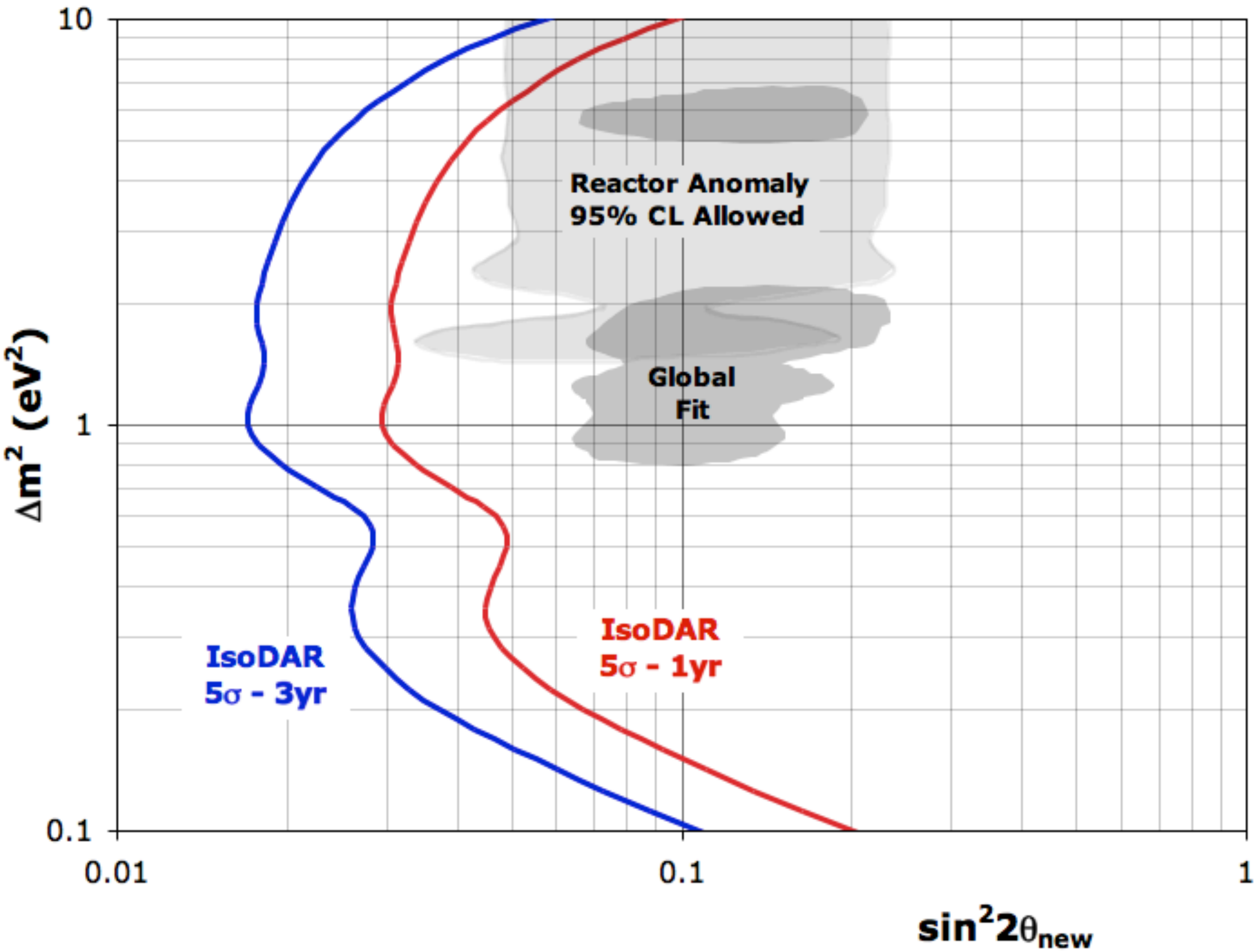


Accelerator	60 MeV/amu of H_2^+
Current	10 mA of protons on target
Power	600 kW
Duty cycle	90%
Run period	5 years (4.5 years live time)
Target	^{9}Be surrounded by ^{7}Li (99.99%)
$\overline{\nu}$ source	^{8}Li β decay ($\langle E_\nu \rangle$=6.4 MeV)
$\overline{\nu}_e$/1000 protons	14.6
$\overline{\nu}_e$ flux	1.29×10^{23} $\overline{\nu}_e$
Detector	KamLAND
Fiducial mass	897 tons
Target face to detector center	16 m
Detection efficiency	92%
Vertex resolution	12 cm/$\sqrt{E}$ (MeV)
Energy resolution	6.4%/$\sqrt{E}$ (MeV)
Prompt energy threshold	3 MeV
IBD event total	8.2×10^5

820,000 IBD events

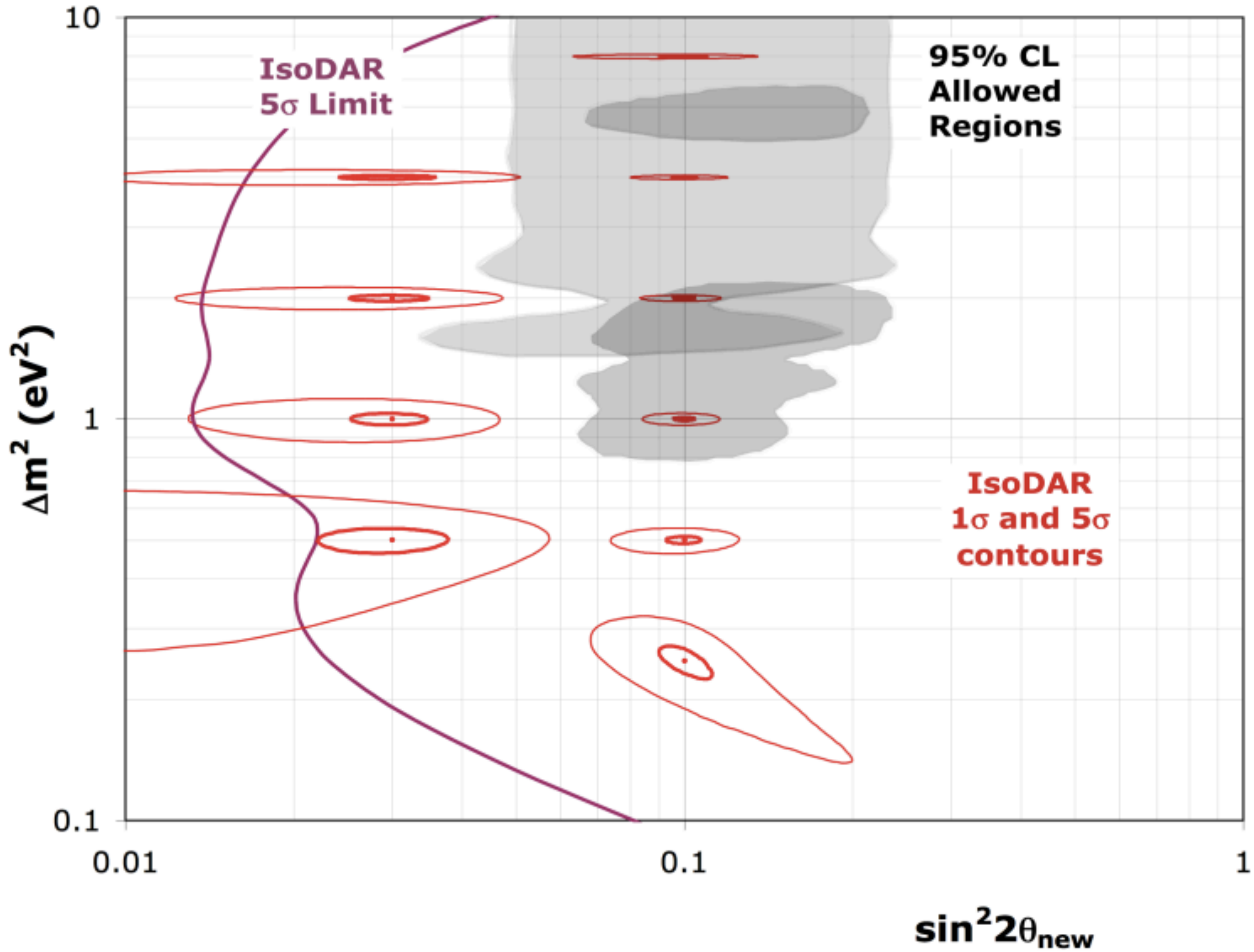
- **Sterile neutrino search**

IsoDAR $\overline{\nu}_e$ Disappearance Oscillation Sensitivity (3+1)



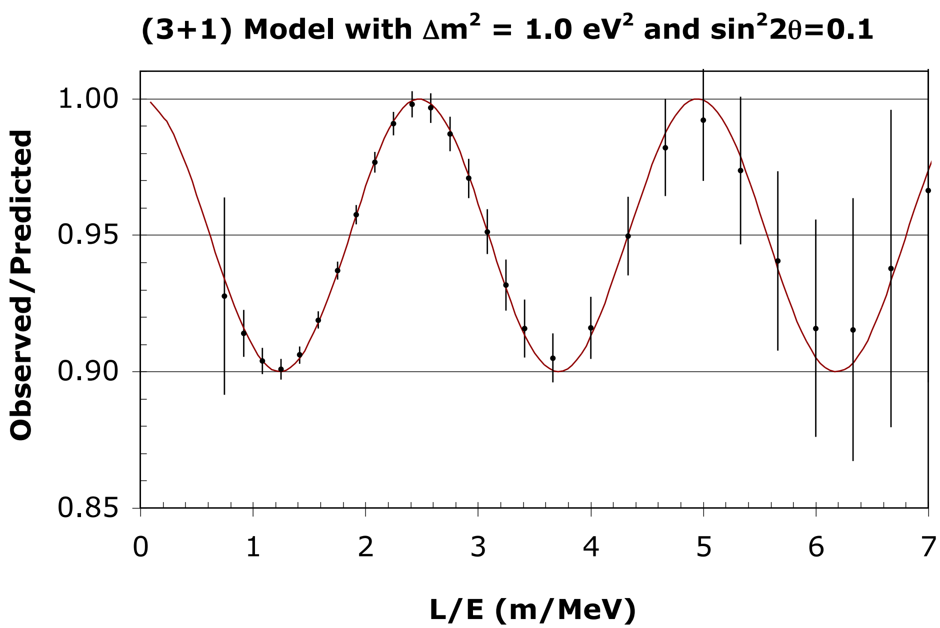
- Global fit can be ruled out at > 5σ in 4 months of running!

IsoDAR Measurement Sensitivity



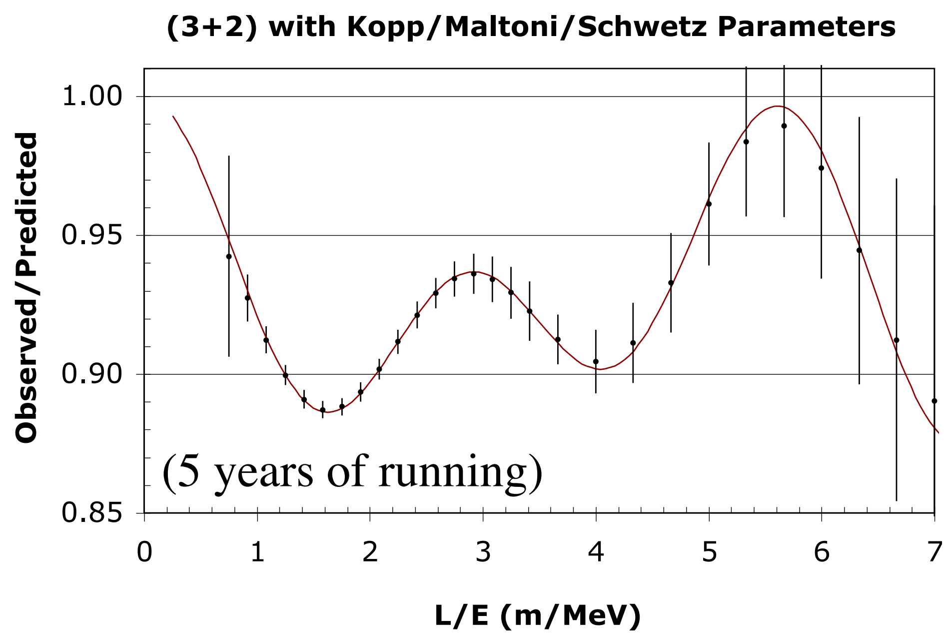
IsoDAR can also discriminate between different sterile neutrino models!

3+1



3+2

PRL 107, 091801(2011)



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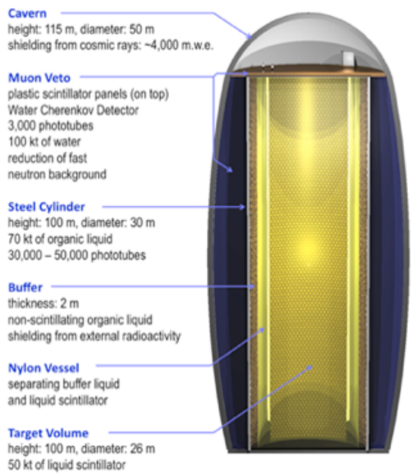

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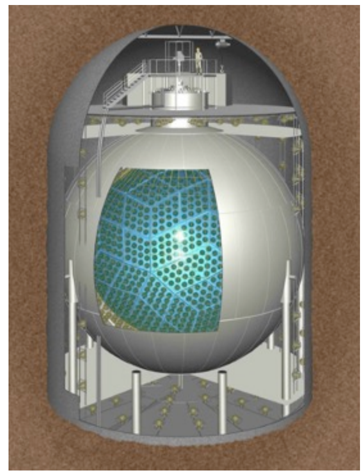

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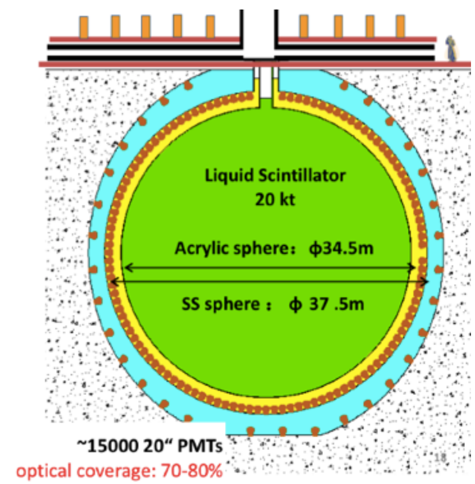

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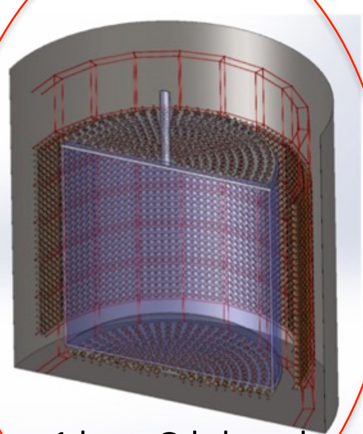

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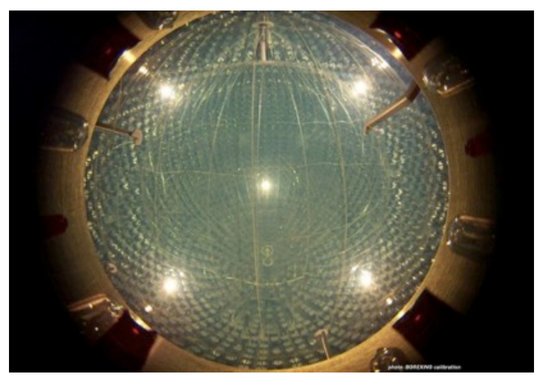

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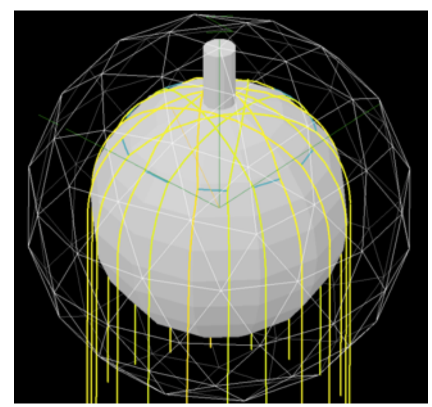
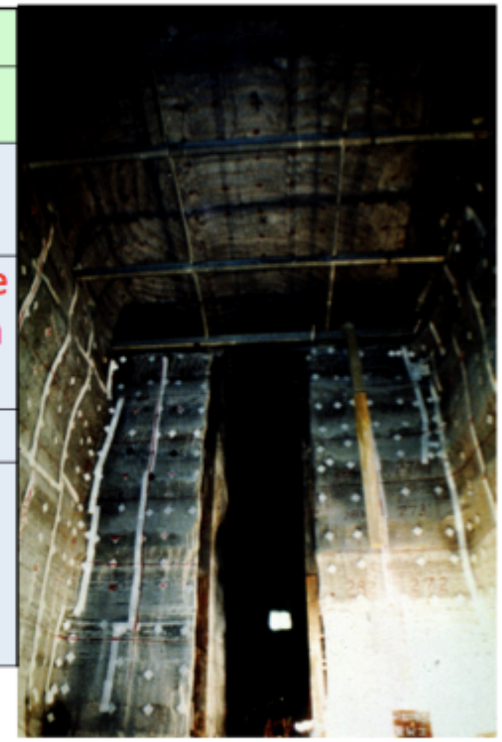
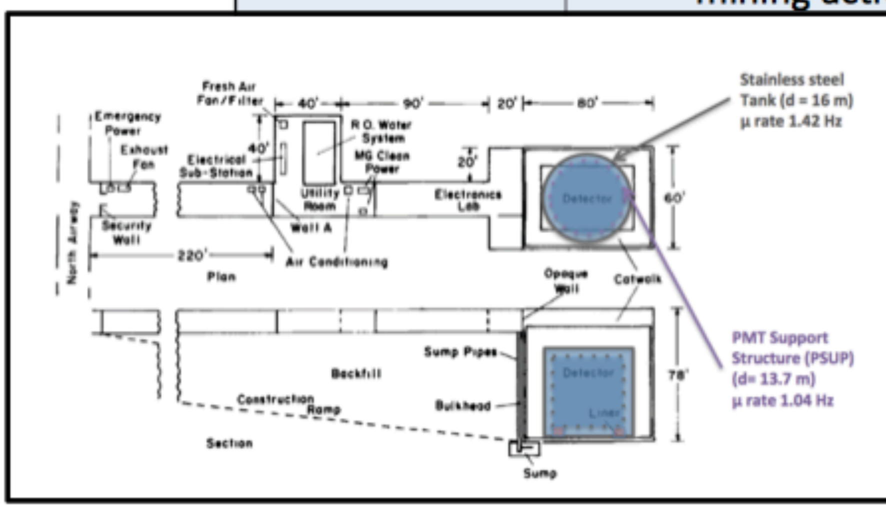


Existing IMB lab only 13 km from commercial nuclear reactor

Reactor Location	Perry Ohio
Thermal Power	3875 MWt
Detector Location	Morton Salt/IMB mine (!) Painesville, Ohio
Standoff	13 km - the only reactor in the US at a suitable distance from a deep mine
Overburden	1670 mwe
Approval status	Morton Salt has approved installation – assuming cost-neutral and no disruption to mining activities



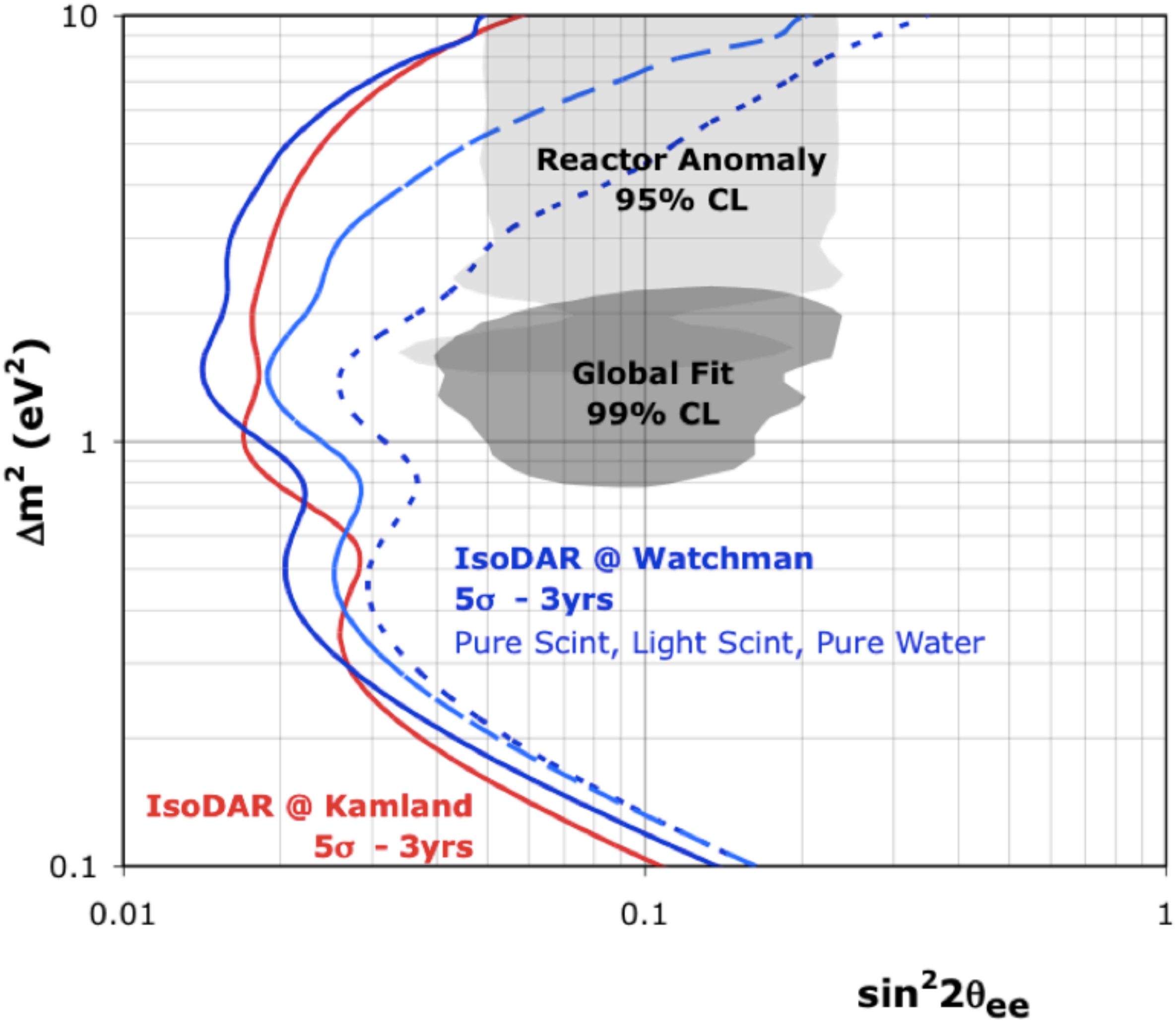


The IMB cavern in late 1970's. Used by DOE HEP from 1960-1990 for the IMB detector and other smaller experiments

WATCHMAN Disappearance Sensitivity

IsoDAR source 6.5 m away from 1 kton Gd-doped (0.1%) H20 fiducial volume

- Also consider water-based light scintillator (1%) and pure scintillator options



Outline

- The Isotope Decay-At-Rest Experiment (IsoDAR)

- IsoDAR Challenges

- $\bar{\nu}_e e$ $(\nu_e e)$ scattering experiments

Challenges of the target

1. Obtaining ~700 kg of ^{7}Li
   ^{7}Li is produced for Molten Salt Reactors as FLiBe
   (need 2.4 tons)

100 m^3 of flibe will contain about 30 tonnes of 99.995% ^{7}Li with previous cost estimates being from 120 to 800 $/kg. Even several

Nuclear Engineering and Design
Volume 240, Issue 6, June 2010, Pages 1644–1656

Molten salt reactors: A new beginning for an old idea

David LeBlanc[a,b,*]

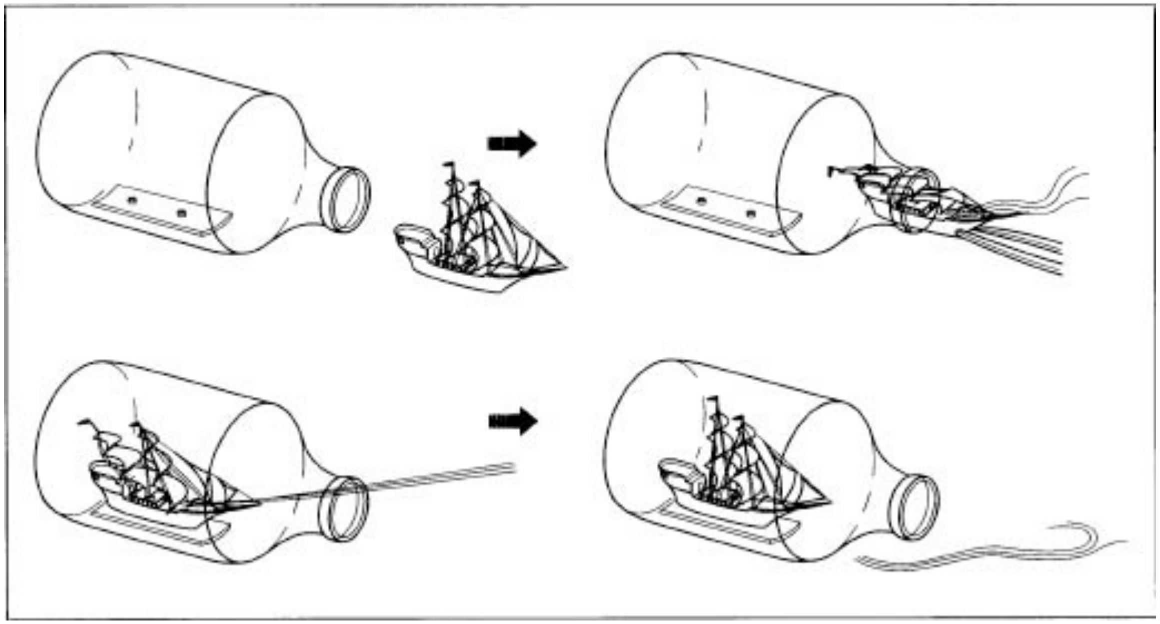
high end of estimate → $2M for IsoDAR

(50 kg are at MIT reactor for study now)

2. Designing the target:
   Under investigation by Bartoszek Engineering

   Targeting – 600 kW "painted"
   across embedded Be target face

A major difference between IsoDAR and existing machines:
the proposed underground installation!



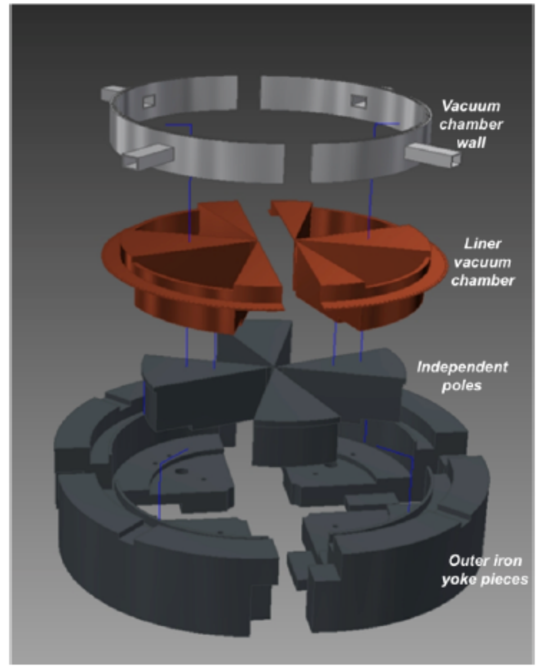


Figure 3 – Cyclotron general split parts

1. Slicing up the cyclotron to bring it in (TRIUMF was sliced)
2. Space for installation/layout of power supplies/etc
3. Shielding issues in a mine

IsoDAR Uses Higher Currents Than Existing Similar Cyclotrons

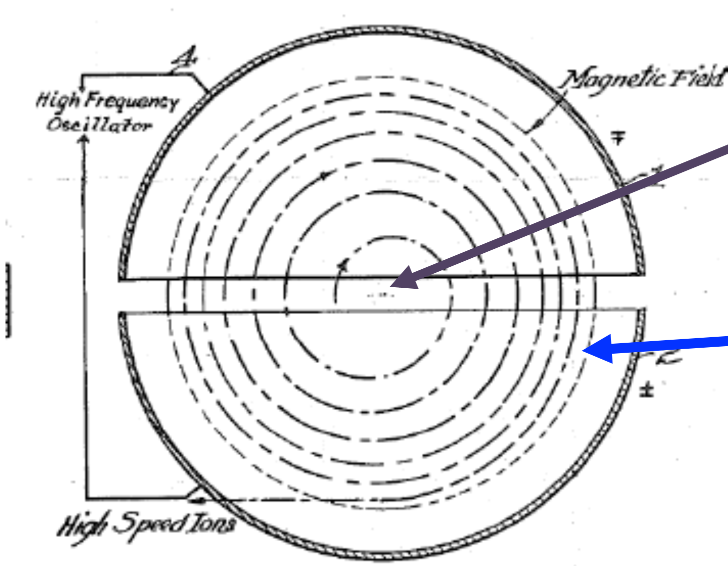
We claim we will be able to produce
~10 mA of protons @ 60 MeV
when commercial machines (IBA, Best) produce
~1 mA of protons @ 70 MeV

How do we achieve this?

Four issues to solve…

1. Space charge
2. Intensity of ion source
3. Inflection from transverse to median plane
4. Extraction from cyclotron (see backups)

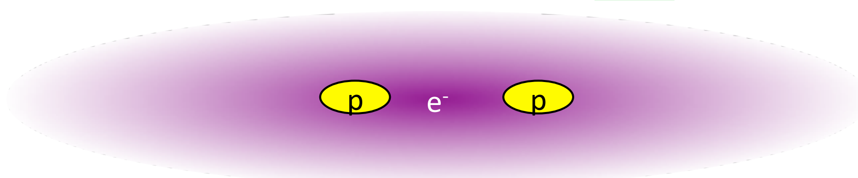
1) Accelerate more particles for same level of space charge



If you inject a lot of charge here, it repels & beam "blows up"

As radii get closer together, bunches at different radii interact

To reduce the "space charge" at injection… we use H_2^+



2 protons per unit of +1 charge

1) Accelerate more particles for same level of space charge

A simplified measure of the strength of space charge is the generalized perveance:

$$K = \frac{qI}{2\pi\varepsilon_0 m\gamma^3\beta^3}$$

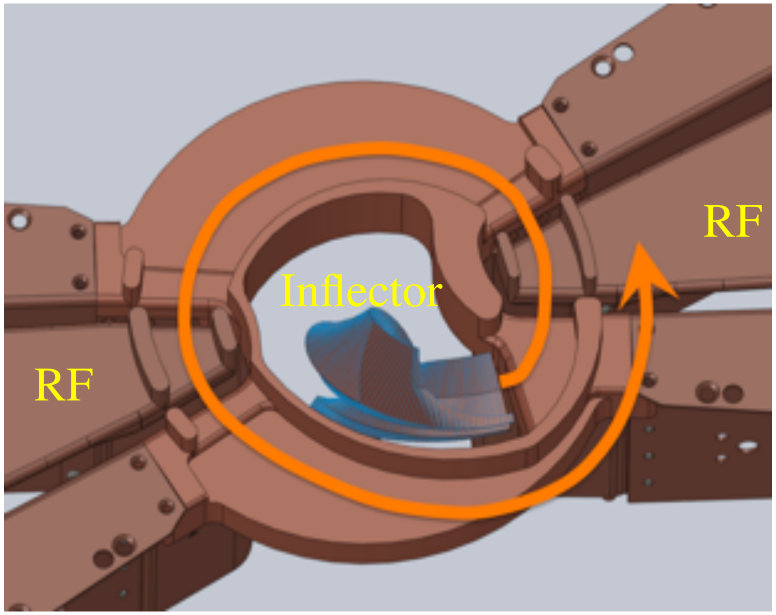
Comparing perveance at injection:
5 mA, 35 keV/n of H2+ = 2 mA, 30 keV of p

(already achieved in commercial cyclotrons)

2) Push the envelope of H_2^+ intensities from ion sources

Most ions are lost in the first "turn" because they hit material.

To capture 5 mA we will need between 35 and 50 mA injected.

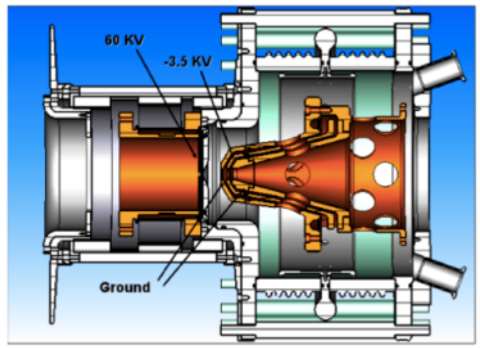


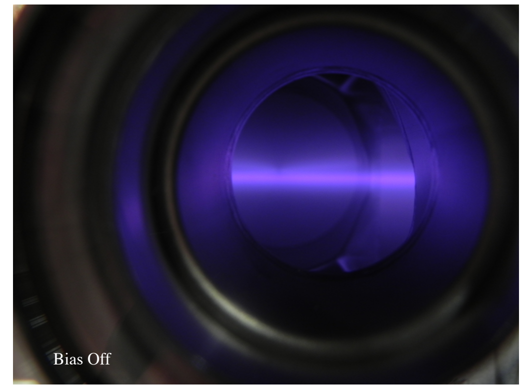
This is not unusual for a p source, but is high for an H_2^+ source. This is at the edge of what has been done…

Two options ion source options:

1) Versatile Ion Source re-optimized for H_2^+

S. Gammino et al., "Tests of the Versatile Ion Source (VIS) for high power proton beam production", ECRIS'10, Grenoble, France





2)

Testing of a H_2^+-enriched ion source for deuterium simulation

M. D. Williams and K. N. Leung

Lawrence Berkeley Laboratory, Berkeley, California 94720

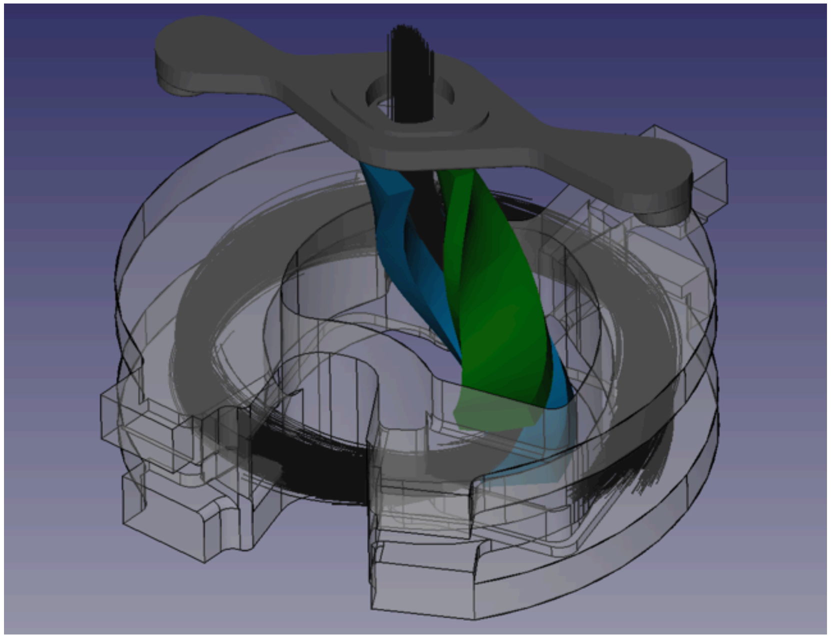
G. M. Brennen and D. R. Burns

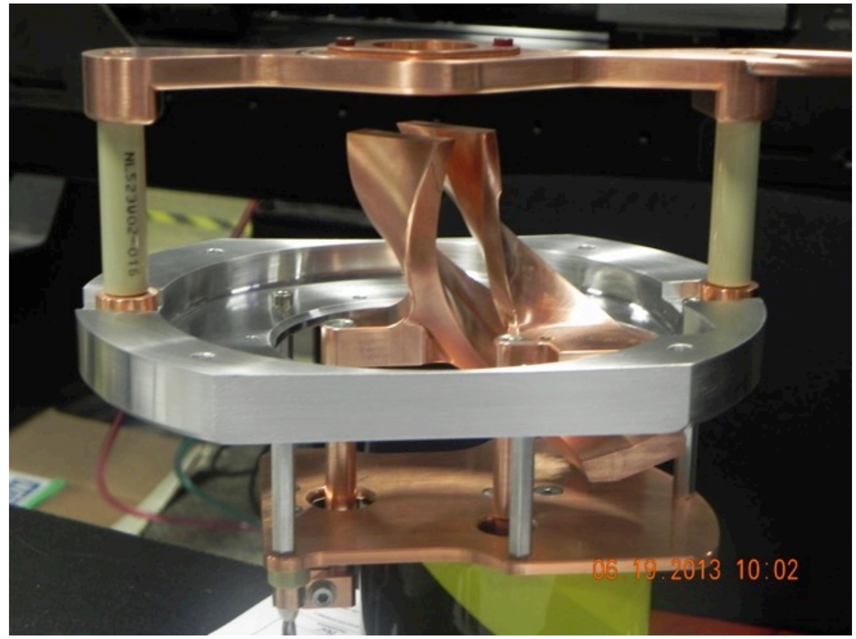
McDonnell Douglas Astronautics Co., St. Louis, Missouri 63166

(Presented on 12 July 1989)

We have tested a McDonnell Douglas short milticusp plasma generator, designed to generate a positive hydrogen ion beam which is enriched with H_2^+ ions. Initial testing shows that the prototype source is capable of producing a positive hydrogen ion beam with H_2^+ percentage greater than 85%. The total ion-current density was 56 mA/cm^2. For a higher current density of 110 mA/cm^2, the percentage of H_2^+ ions is approximately 73% as measured by a magnetic deflection spectrometer. A comparison between tungsten and lanthanum hexaboride cathodes shows that tungsten filaments can provide better performance.

3) Develop an unusually large spiral inflector (H_2^+ rigidity)

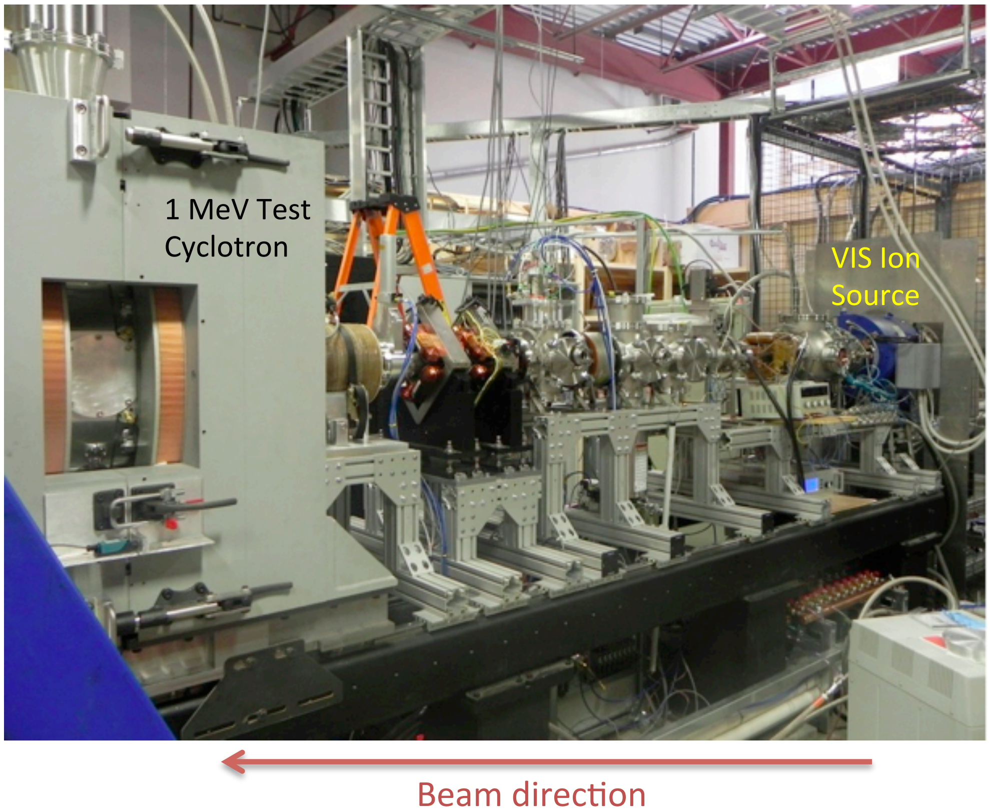


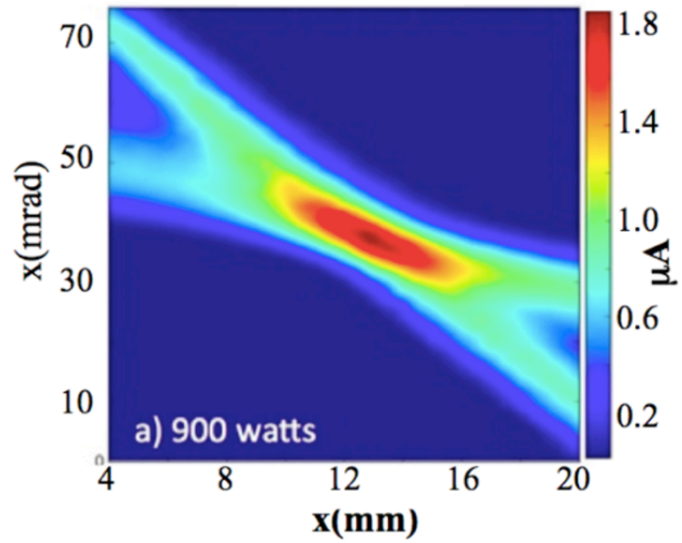


Tricky to design:
- B field effects
- Space charge

This is an iterative R&D process

These Issues Studied In Test Beam Experiments at Best Cyclotrons Systems, Inc





Beam and source characterized

- Emittance measurements
- Space charge compensation
- Inflection and capture

International Partnership Between Universities, Labs, and Industry
(Best Cyclotron Systems, INFN-Catania, and MIT -- NSF funded)

IsoDAR Cyclotron: Medical Isotopes

Isotope	half-life	Use
^{52}Fe	8.3 h	The parent of the PET isotope ^{52}Mn and iron tracer for red-blood-cell formation and brain uptake studies.
^{122}Xe	20.1 h	The parent of PET isotope ^{122}I used to study brain blood-flow.
^{28}Mg	21 h	A tracer that can be used for bone studies, analogous to calcium
^{128}Ba	2.43 d	The parent of positron emitter ^{128}Cs. As a potassium analog, this is used for heart and blood-flow imaging.
^{97}Ru	2.79 d	A γ-emitter used for spinal fluid and liver studies.
^{117m}Sn	13.6 d	A γ-emitter potentially useful for bone studies.
^{82}Sr	25.4 d	The parent of positron emitter ^{82}Rb, a potassium analogue This isotope is also directly used as a PET isotope for heart imaging.

IsoDAR Cyclotron: Medical Isotopes

Isotope	half-life	
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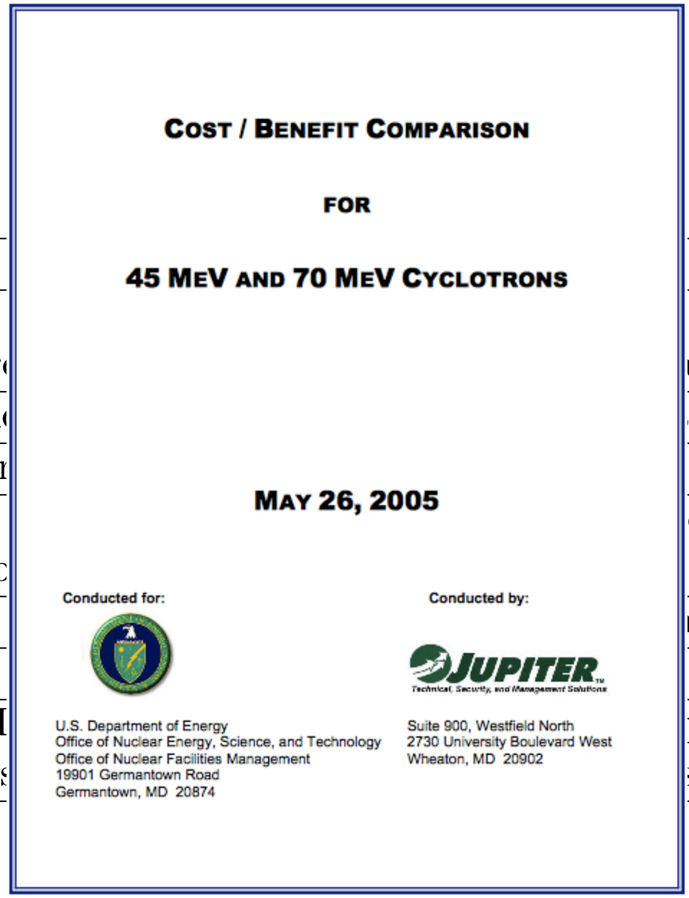
COST / BENEFIT COMPARISON

FOR

45 MEV AND 70 MEV CYCLOTRONS

MAY 26, 2005

Conducted for:

U.S. Department of Energy
Office of Nuclear Energy, Science, and Technology
Office of Nuclear Facilities Management
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Germantown, MD 20874

Conducted by:

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The Department of Energy's (DOE) Office of Nuclear Energy, Science, and Technology (NE) asked *JUPITER* Corporation (*JUPITER*) to conduct a cost comparison between 45 MeV and 70 MeV negative ion (H$^-$) cyclotrons to help support an NE decision on the potential purchase of an accelerator for the production of medical radioisotopes. We have conducted a survey of accelerator manufacturers and

How much does such a cyclotron cost?

INFN

ISODAR budget Report

August 2014
Page 1

ISODAR Injector Cyclotron Budget Report

Prepared by: INFN	Prepared by: IBA *Michel Abs*, *Albert Blondin*, *Eric Forton*, *Benoit Nactergal*, *Thomas Servais*
Keywords:	

Contents

Cost for the first
Cyclotron (on surface): <$21M

Does not include extra cost to install underground or cost of the target.

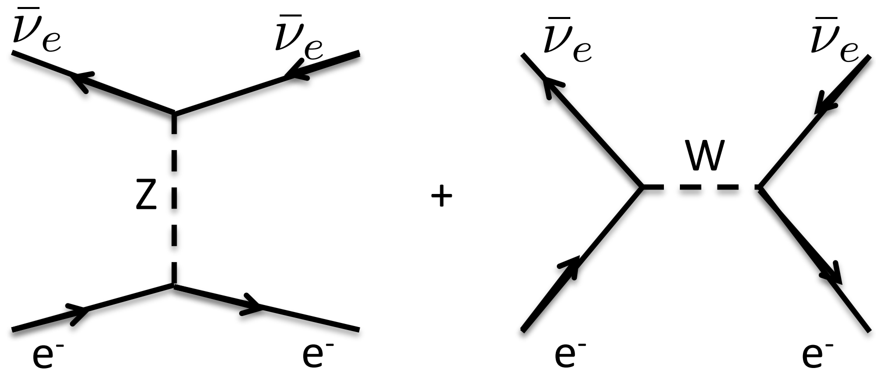
→ $1M engineering R&D needed to produce CDR to submit to funding agencies

Opens up possibility to produce a new type of neutrino source

Outline

- The Isotope Decay-At-Rest Experiment (IsoDAR)
- IsoDAR Challenges
- $\bar{\nu}_e e\ \ (\nu_e e)$ scattering experiments

$\bar{\nu}_e e$ scattering—g_V, g_A, $\sin^2\theta_W$



$$g_L = \tfrac{1}{2}(g_V + g_A)$$
$$g_R = \tfrac{1}{2}(g_V - g_A)$$

For $\nu_e e$ scattering,
$g_L \leftrightarrow g_R$

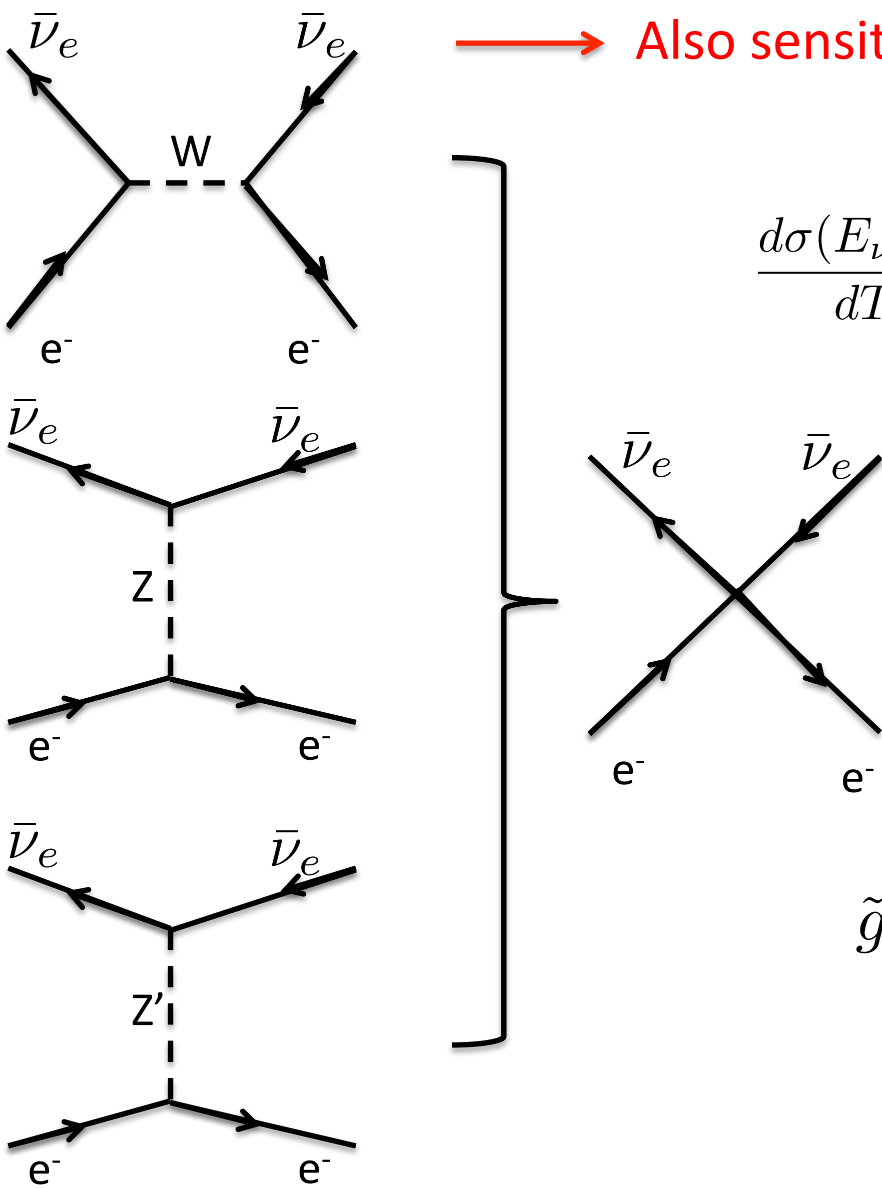
$$\frac{d\sigma}{dT} = \frac{2G_F^2 m_e}{\pi}\left[g_R^2 + g_L^2\left(1 - \frac{T}{E_\nu}\right)^2 - g_R g_L \frac{m_e T}{E_\nu^2}\right]$$

$$g_L = \frac{1}{2} + \sin^2\theta_W; \quad g_R = \sin^2\theta_W$$

Precisely-known standard model cross section

→ Sensitive to g_V, g_A, $\sin^2\theta_W$

$\bar{\nu}_e e$ scattering—NSIs



→ Also sensitive to nonstandard interactions (NSIs)

$$\frac{d\sigma(E_\nu,T)}{dT} = \frac{2G_F^2 m_e}{\pi}\Big[(\tilde{g}_R^2 + \sum_{\alpha\neq e}|\epsilon_{\alpha e}^{eR}|^2) + (\tilde{g}_L^2 + \sum_{\alpha\neq e}|\epsilon_{\alpha e}^{eL}|^2)\left(1-\frac{T}{E_\nu}\right)^2 - (\tilde{g}_R\tilde{g}_L + \sum_{\alpha\neq e}|\epsilon_{\alpha e}^{eR}||\epsilon_{\alpha e}^{eL}|)m_e\frac{T}{E_\nu^2}\Big]$$

$$\tilde{g}_L = g_L + \epsilon_{ee}^{eL} \qquad \tilde{g}_R = g_R + \epsilon_{ee}^{eR}$$

$\bar{\nu}_e e$ scattering

- Elastic scattering signal
  - Single isolated event
  - Recoil electron points back to source (energy dependent)
  - Energy spectrum piles up at low energy
    - Precision electroweak tests primarily from rate

- Non beam-related backgrounds
  - Spallation isotopes produced from cosmics
  - Natural radioactivity (internal and external)
  - Solar neutrinos!
  - All these can be measured and subtracted

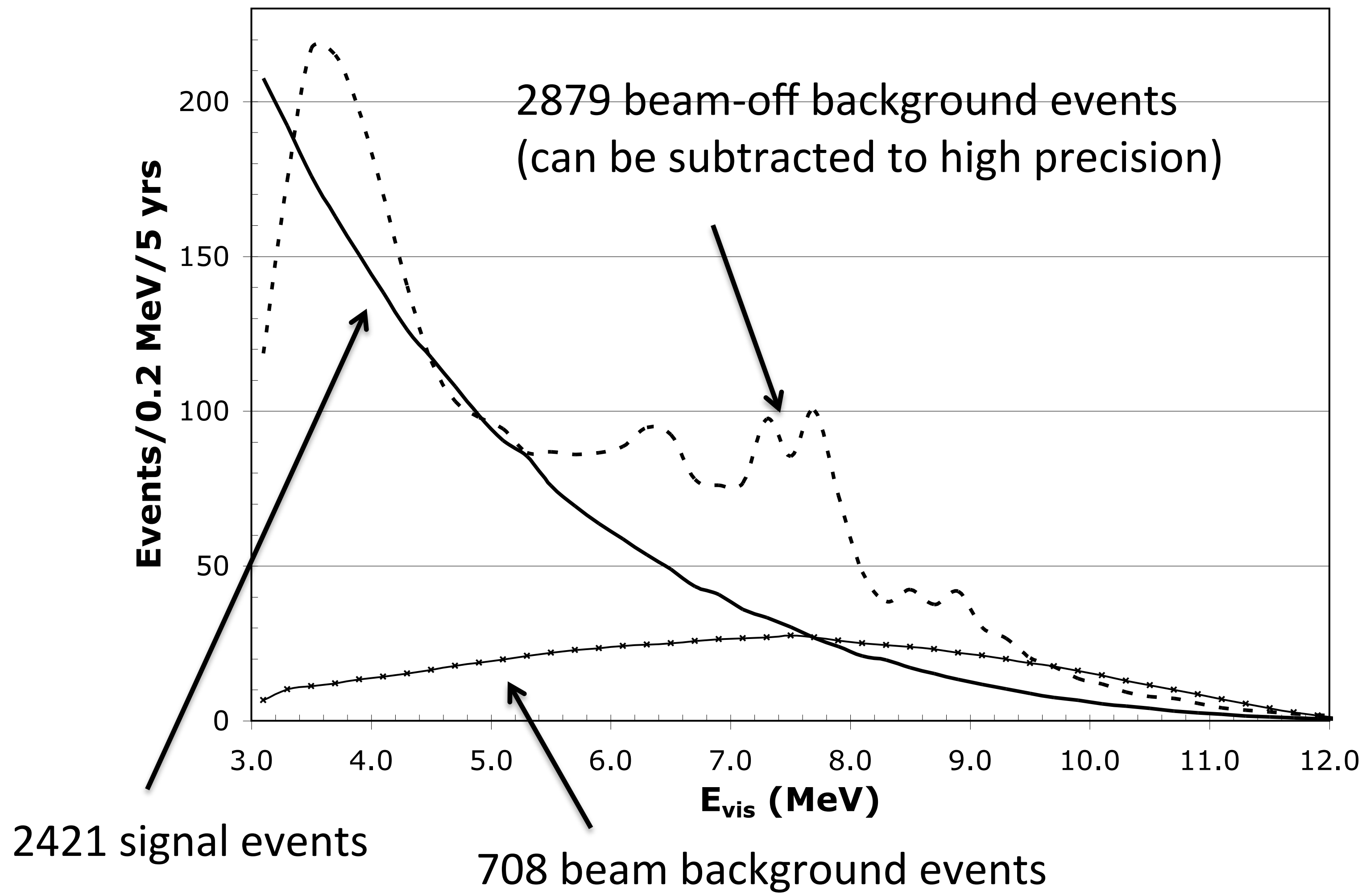
- Beam-related backgrounds ($\bar{\nu}_e e$ scattering)
  - Misidentified IBD events

$\bar{\nu}_e e$ scattering

- Elastic scattering signal
  - Single isolated event
  - Recoil electron points back to source (energy dependent)
  - Energy spectrum piles up at low energy
    - Precision electroweak tests primarily from rate ← Measure source rate or normalize to IBDs
- Non beam-related backgrounds
  - Spallation isotopes produced from cosmics ← Long muon veto
  - Natural radioactivity (internal and external) ← E_{thresh}, Fiducialize
  - Solar neutrinos! ← Directionality?
  - All these can be measured and subtracted
- Beam-related backgrounds ($\bar{\nu}_e e$ scattering)
  - Misidentified IBD events ← Loose IBD selection

IsoDAR $\bar{\nu}_e e$ scattering at KamLAND

2,400 $\overline{\nu}_e$e events above 3 MeV in 5 years of running



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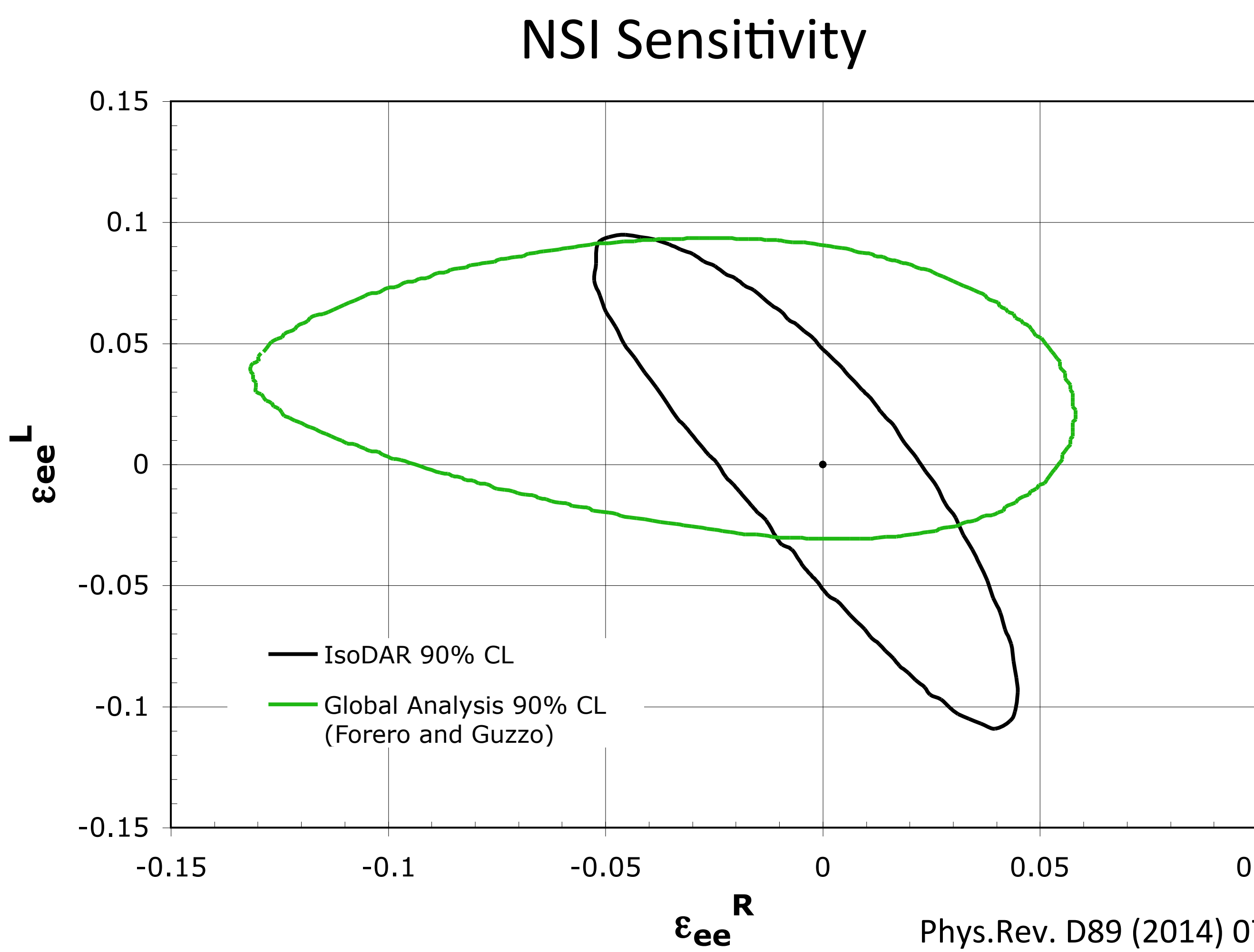

Phys.Rev. D89 (2014) 072010

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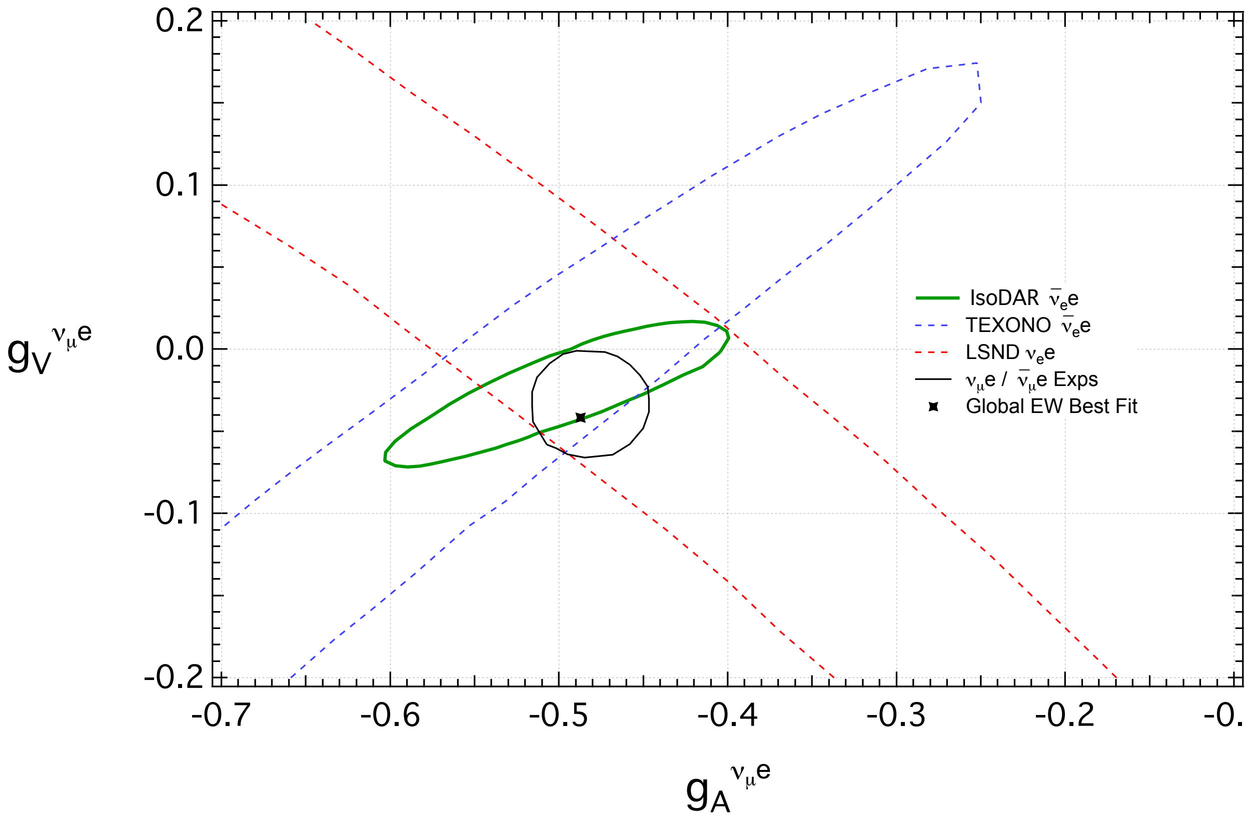
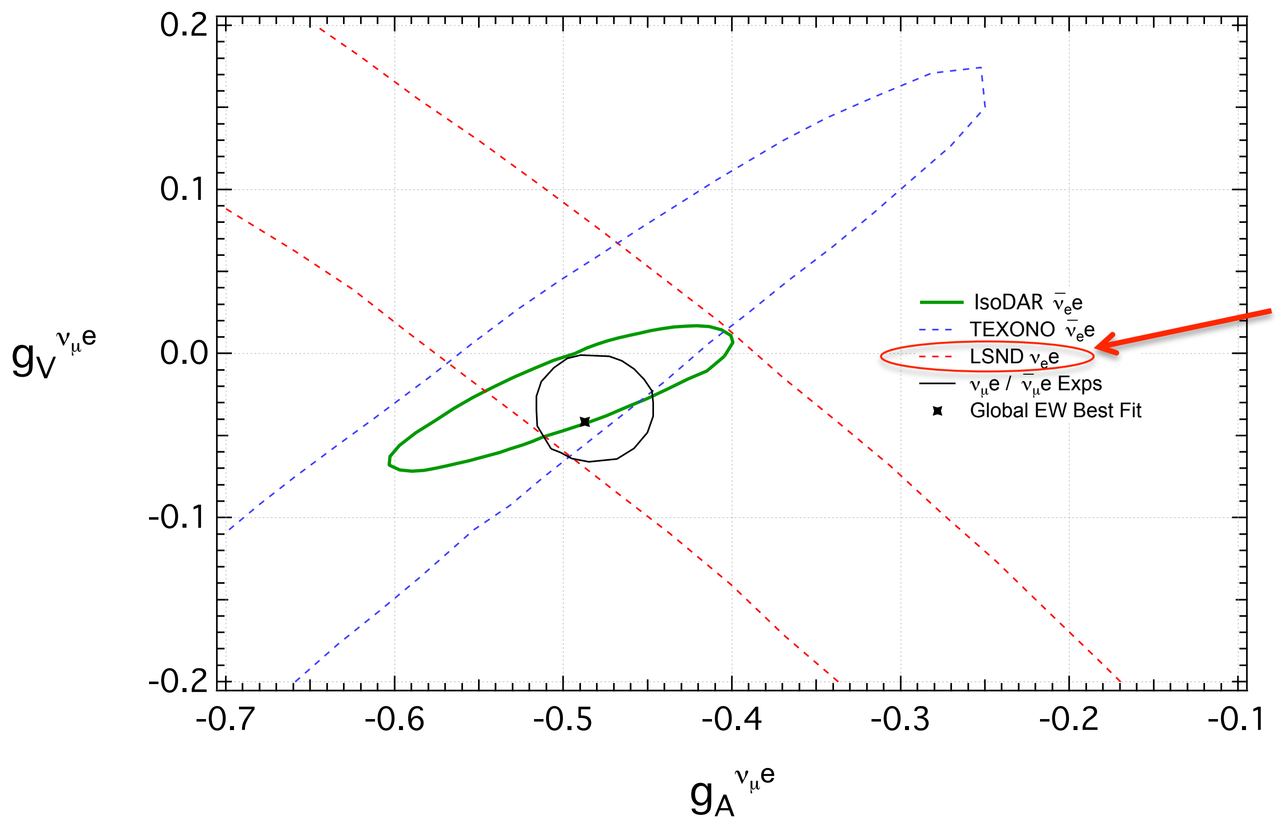


Can also measure $\sin^2\theta_W$ to 3.2%

IsoDAR $\bar{\nu}_e e$ scattering at KamLAND

2,400 $\bar{\nu}_e$e events above 3 MeV in 5 years of running

Phys.Rev. D89 (2014) 072010

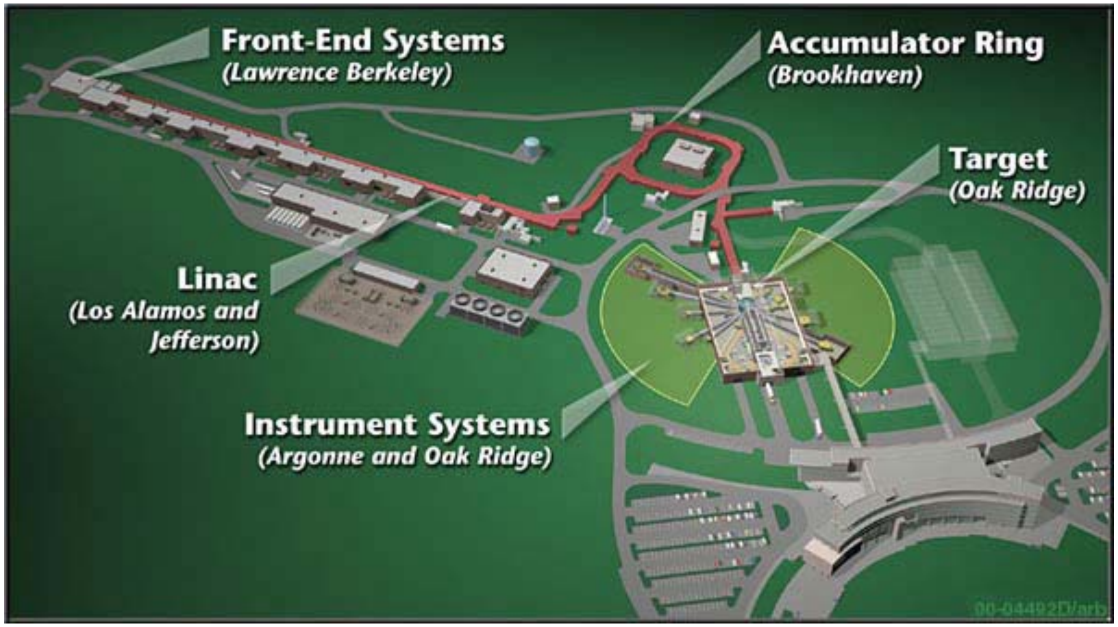


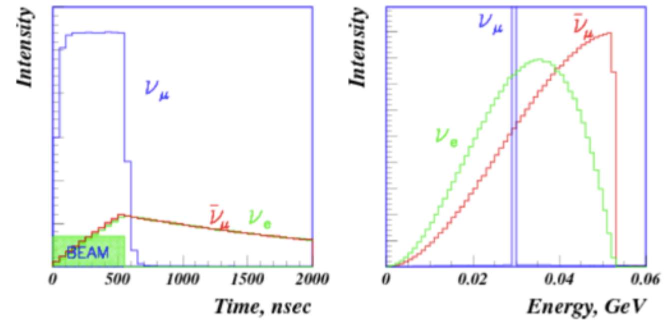
From 191 events

PRD63 112001

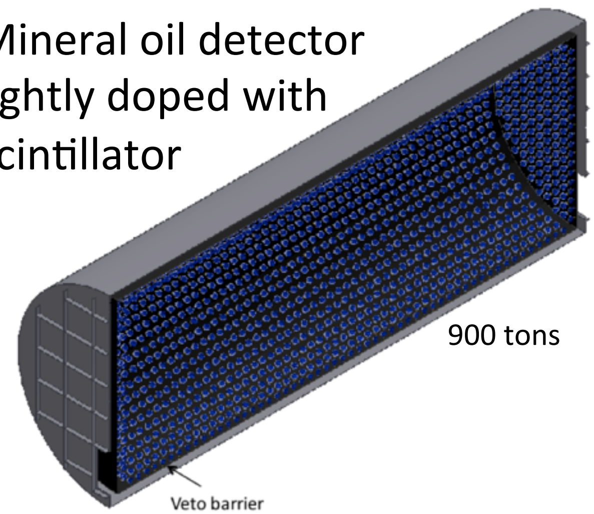
OscSNS

Located 60 m from 1.4 MW spallation neutron source





Mineral oil detector lightly doped with scintillator



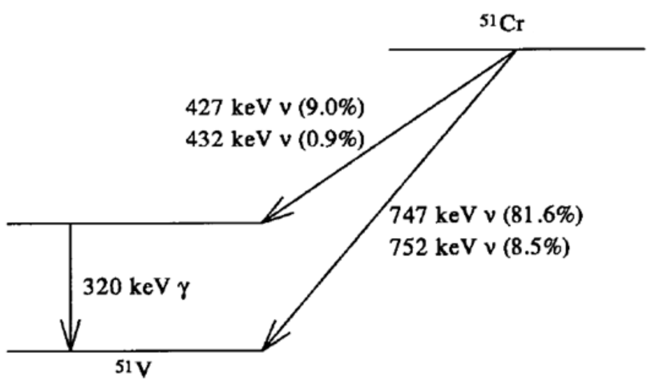
Expect 677 ± 39 $\nu_e e$ events per year

→ Expect to improve on LSND g_V-g_A limits

Radioactive sources

^{51}Cr (τ=40 days)

Produced from thermal neutron capture on Cr enriched in ^{50}Cr



Decay scheme of ^{51}Cr to ^{51}V through electron capture.

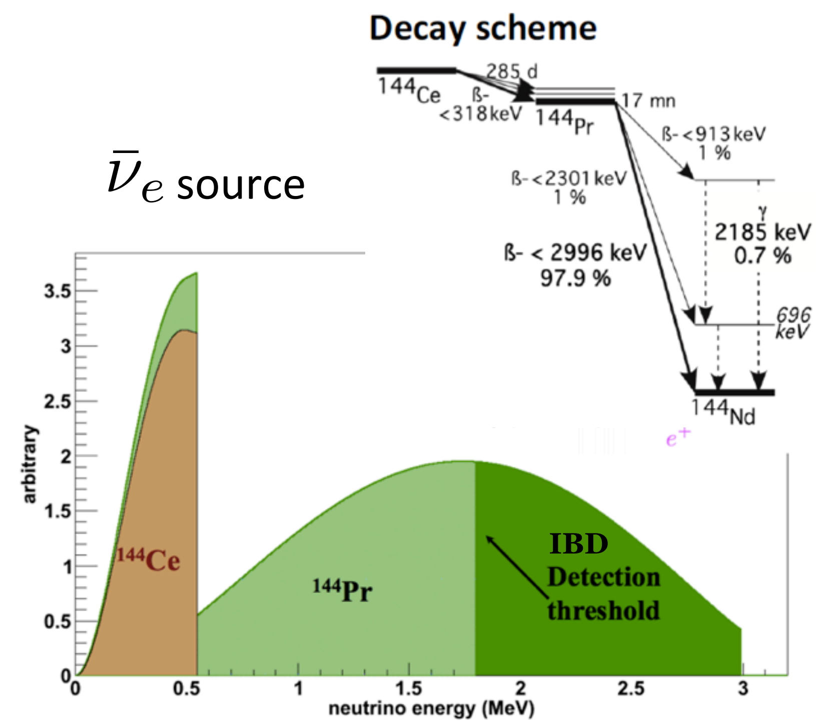
Mono-energetic 750 keV ν_e 90% of the time

GALLEX ^{51}Cr source activity: 62.5 ± 0.4 PBq

^{144}Ce-^{144}Pr (τ=411 days)

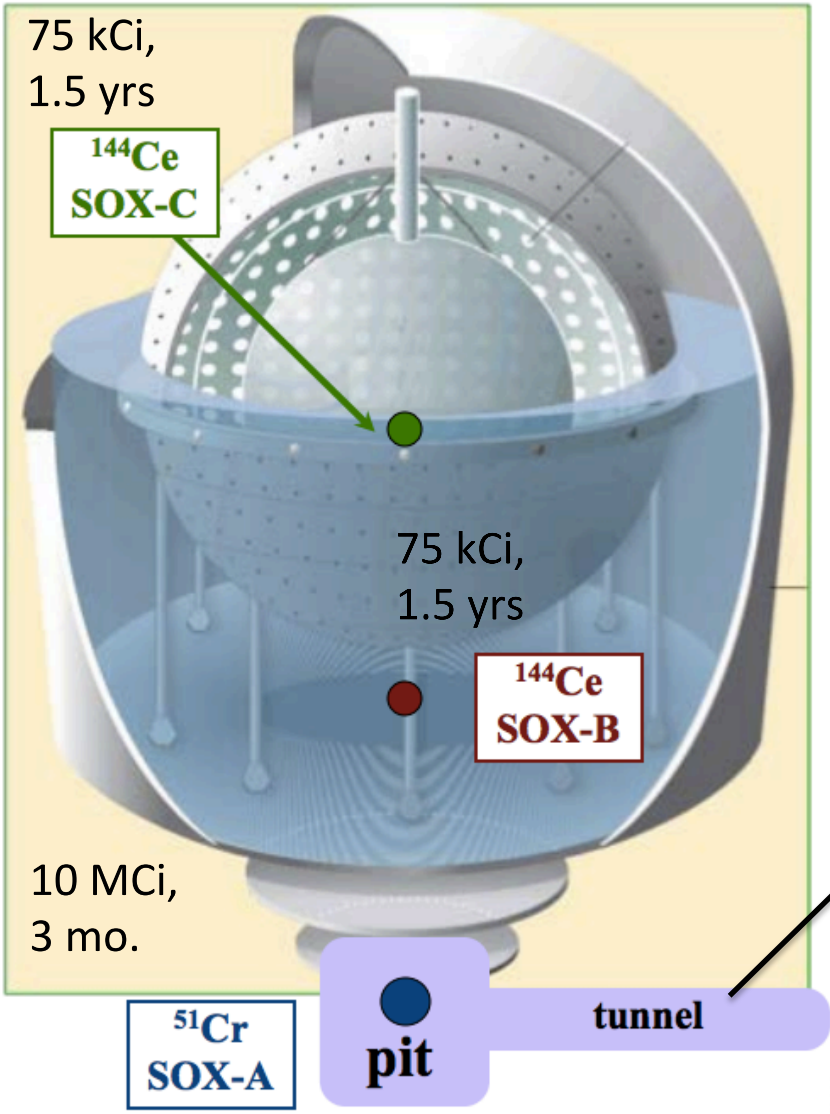
Produced via chemical extraction from spent nuclear fuel

$\bar{\nu}_e$ source



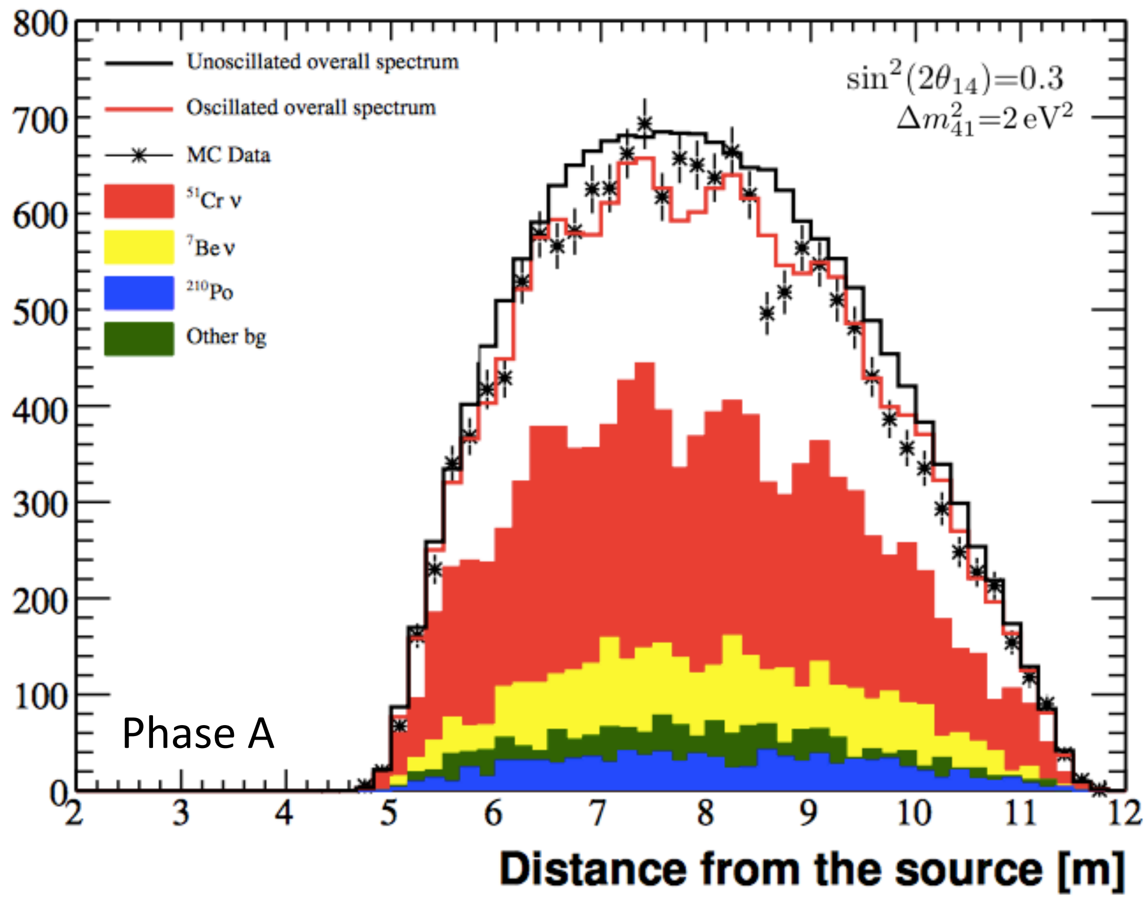
Assume activity measured to 1.5%

Radioactive Sources at Borexino (SOX)



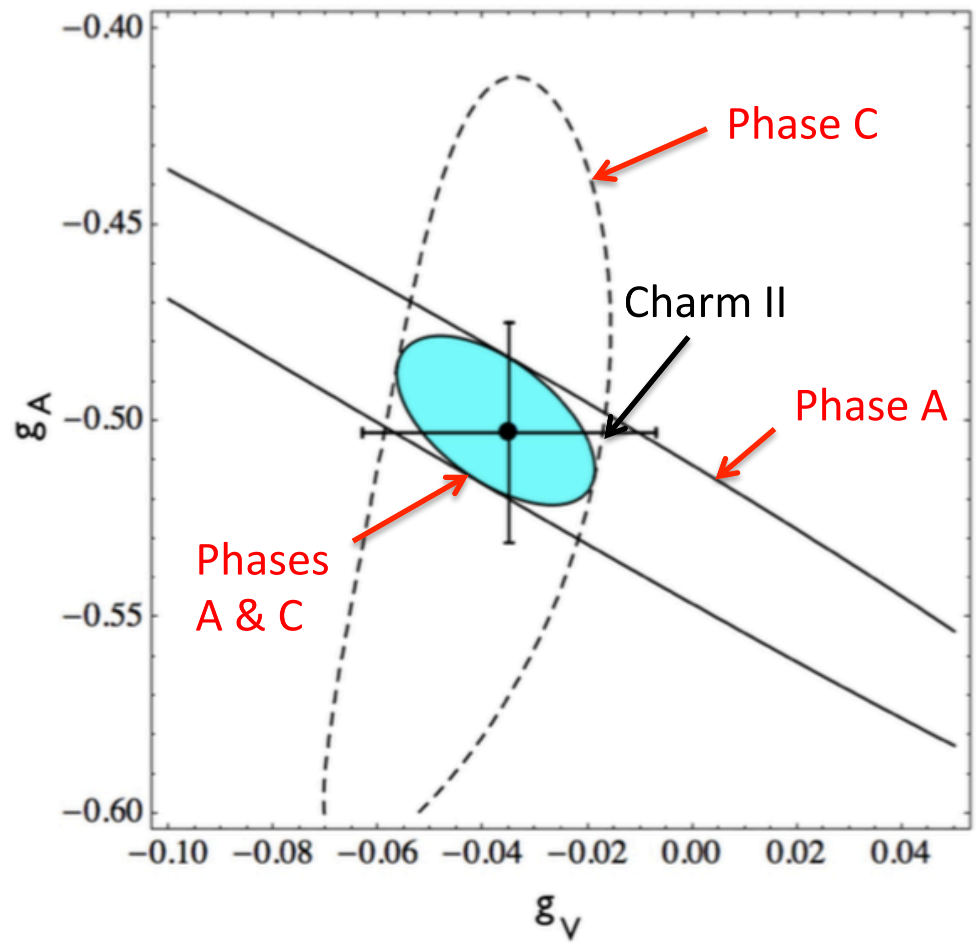
JHEP 1308 (2013) 038

Radioactive Sources at Borexino (SOX)



Borexino backgrounds and detector model calibrated to 1%

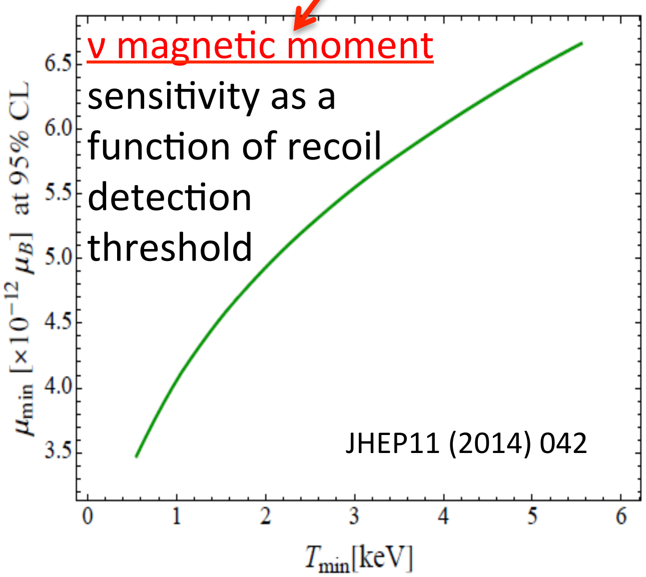
Radioactive Sources at Borexino (SOX)

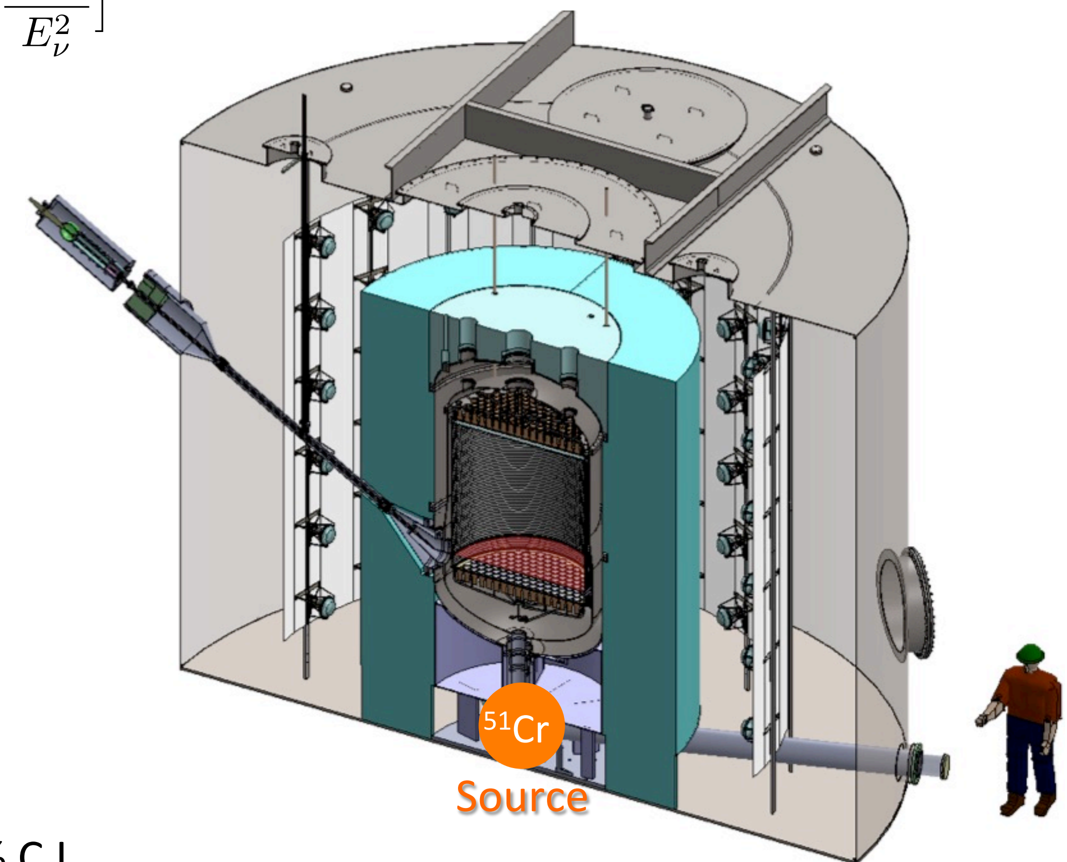


→ Would really like to see more published details of this analysis

5 MCi ^{51}Cr Source For 100 days at LZ

$$\frac{d\sigma}{dT} = \frac{2G_F^2 m_e}{\pi}[g_R^2 + g_L^2(1-\frac{T}{E_\nu})^2 - g_R g_L \frac{m_e T}{E_\nu^2}] + \frac{\pi\alpha_{em}^2 \mu_\nu^2}{m_e^2}[\frac{1-T/E_\nu}{T}]$$





Lab limit: $|\mu_\nu| < 2.9 \times 10^{-11}\,\mu_B$ at 90% C.L.

Adv.High Energy Phys. 2012 (2012) 350150

Astrophysical limit: $\mu_\nu \lesssim 3 \times 10^{-12} \mu_B$

Phys. Rept. 320 (1999) 319-327

1 m below ~6 tons of LXe (cylinder 137.2 cm diameter, 137.2 cm height)

Conclusions

- IsoDAR is a definitive sterile neutrino search
  - Global allowed region excluded at 5σ in 4 months
  - "Smoking gun" oscillation waves reconstructed in detector
  - Measurement sensitivity to sterile ν oscillation parameters
  - Differentiates between 3+1 and 3+2 scenerios

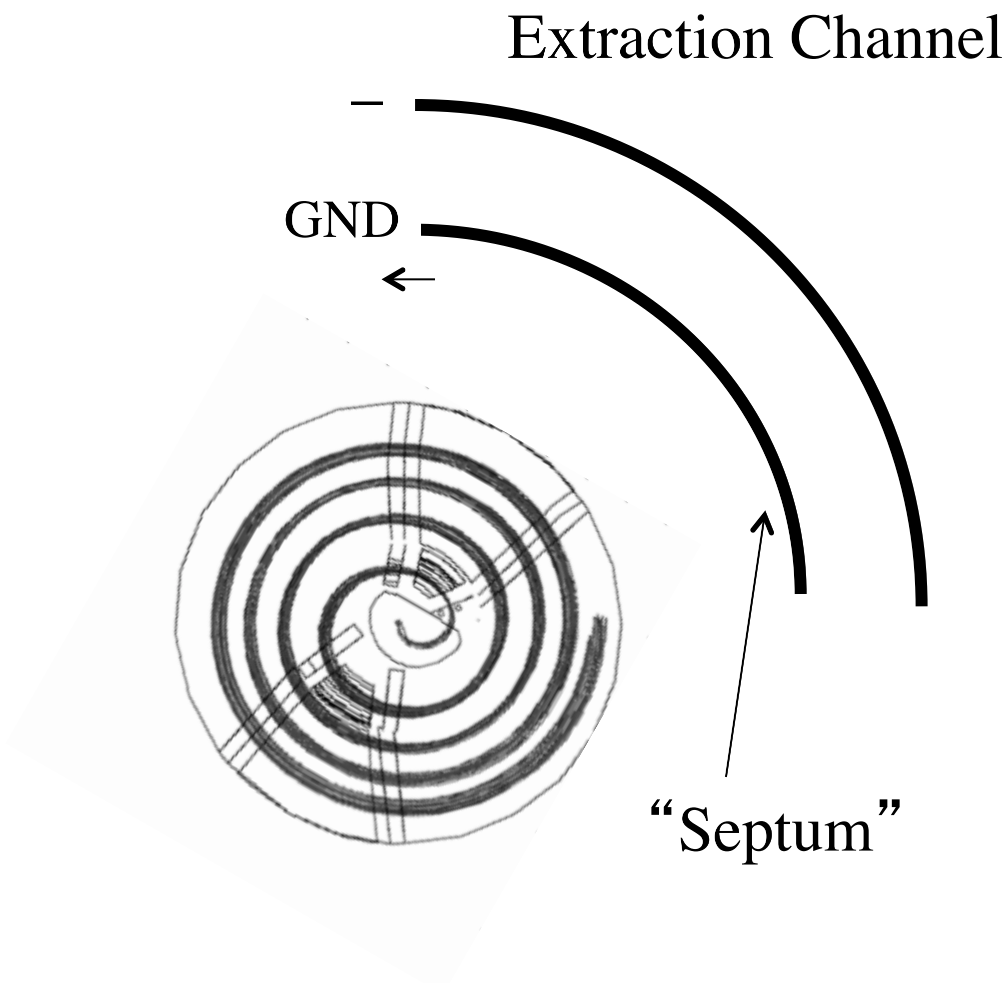
- Lots of progress on IsoDAR's technical challenges

- Precise electroweak tests, NSI searches possible at IsoDAR

- SOX's combined three phases probe both $\nu_e e$ and $\bar{\nu}_e e$ scattering and also allows precise electroweak test, NSI searches. ^{51}Cr source can also probe νMM at DM detectors

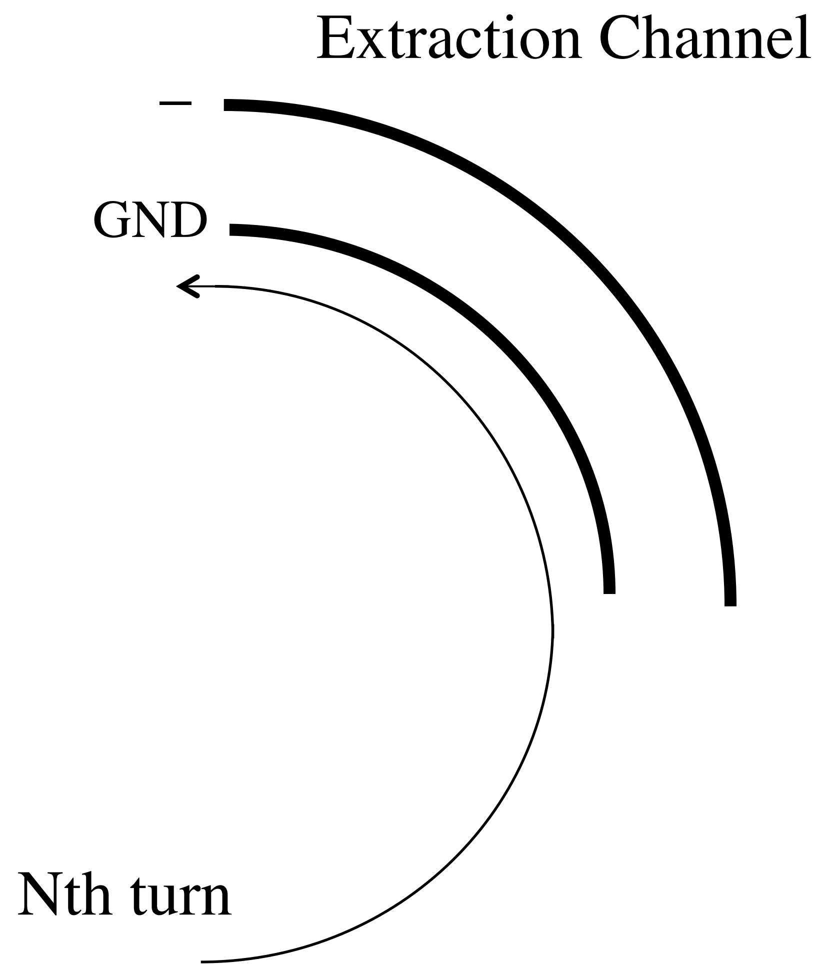
End.

Extraction Process

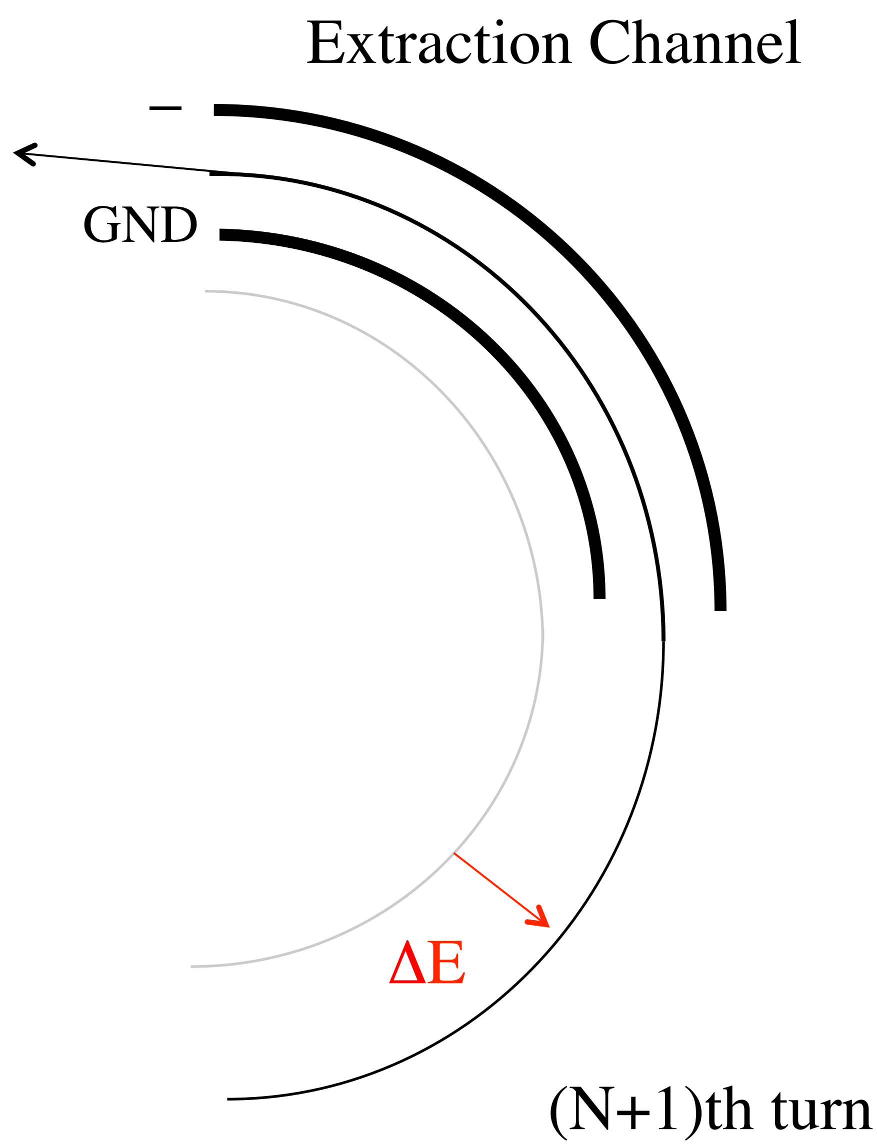


4) Avoid beam losses on the electrostatic extraction septum (protecting with a stripper foil, removing 50 μA of beam)

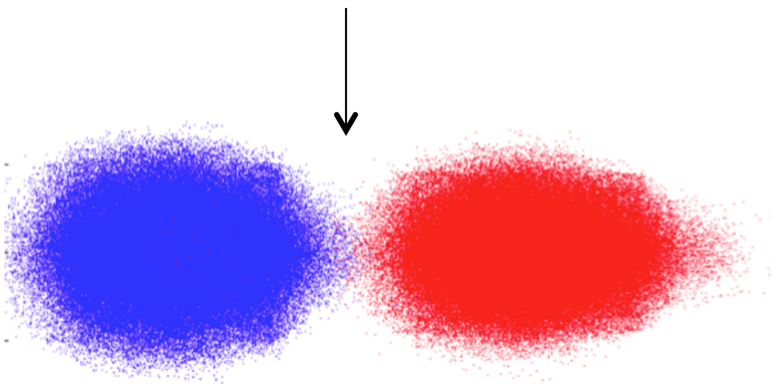
Extraction Process



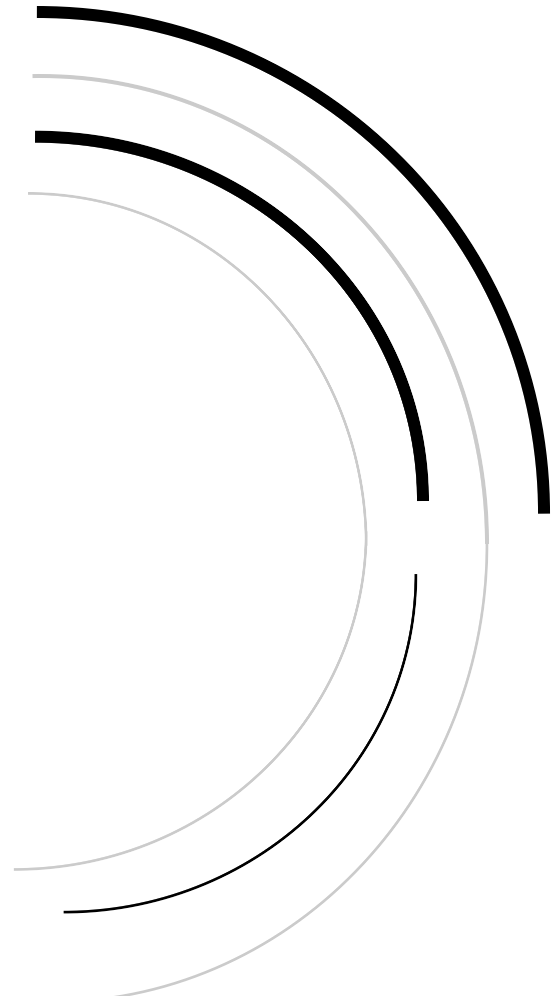
Extraction Process



Extraction Process



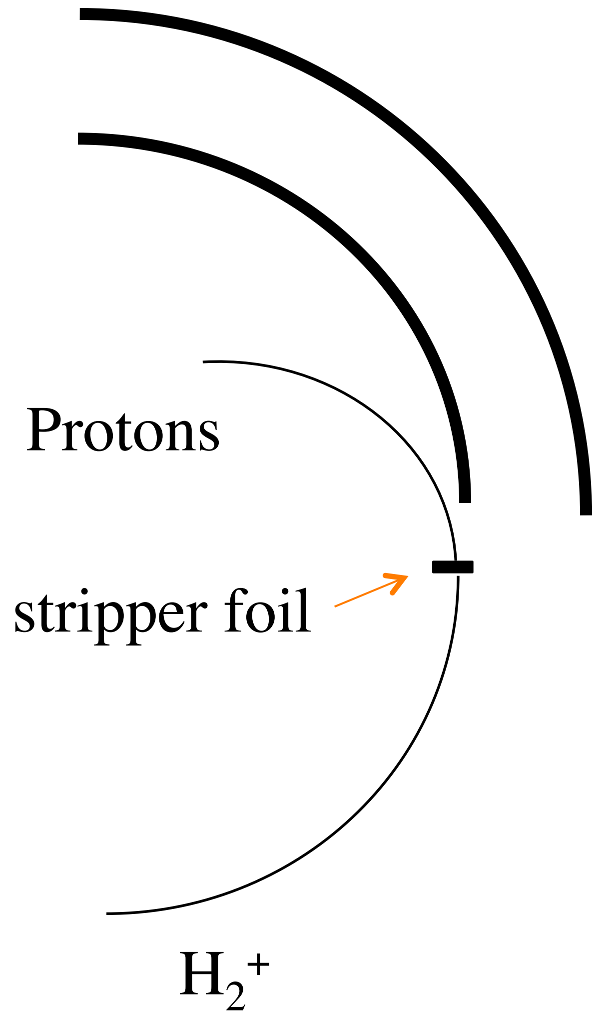
~0.02% intercepted
on septum



"Problem"
(120 W max)

Extraction Process

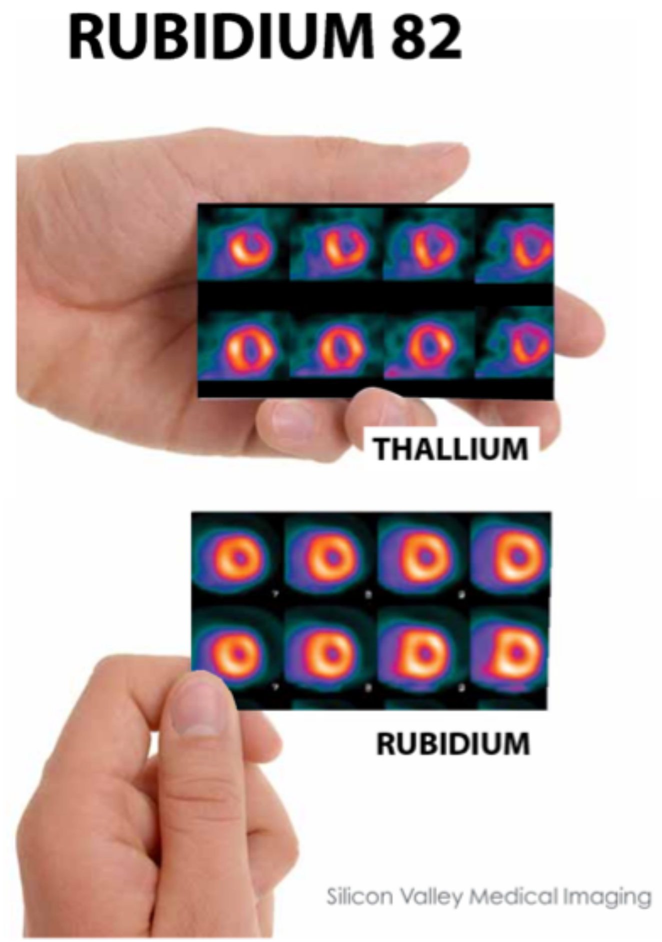
Notice protons
cross the
cyclotron
to exit!
That's ok!



The 50 μA of extracted beam from the foil can be used…

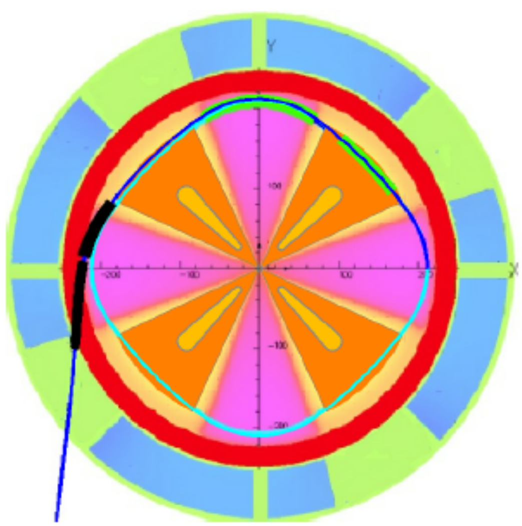
This is the beam energy and intensity that pharmaceutical companies need to produce $^{82}Sr \rightarrow {}^{82}Rb$

Can we offset some cost of running, by collaborating with a company on producing ^{82}Sr?



IsoDAR Cyclotron Design

- Non-superconducting, single coil design [PRL. 109, 141802]
- Accelerates 5mA H_2^+ to 60 MeV/amu (600 kW proton beam)
- Beam dynamics simulated using OPAL code [Nucl.Instrum.Meth. A704 (2013) 84-91]
  - Verified single turn extraction with 'classical' electrostatic septum

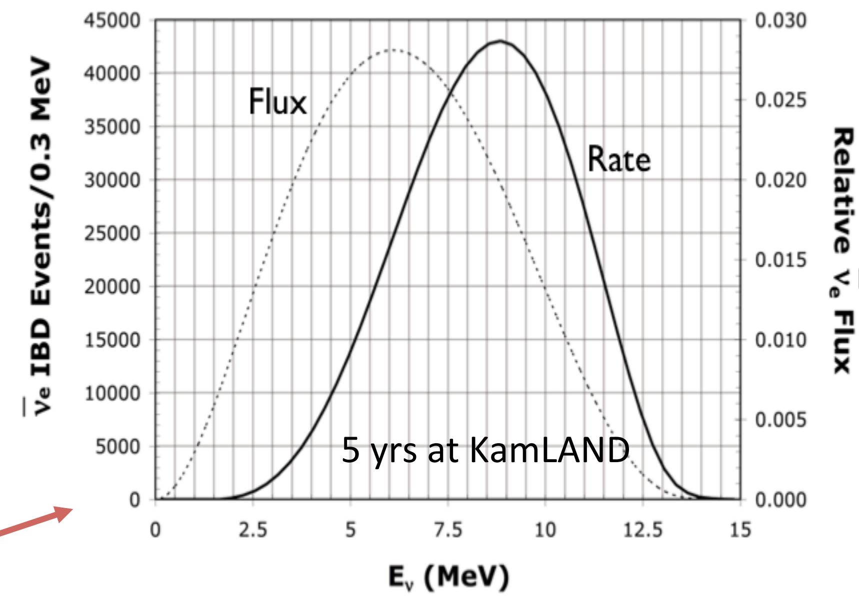


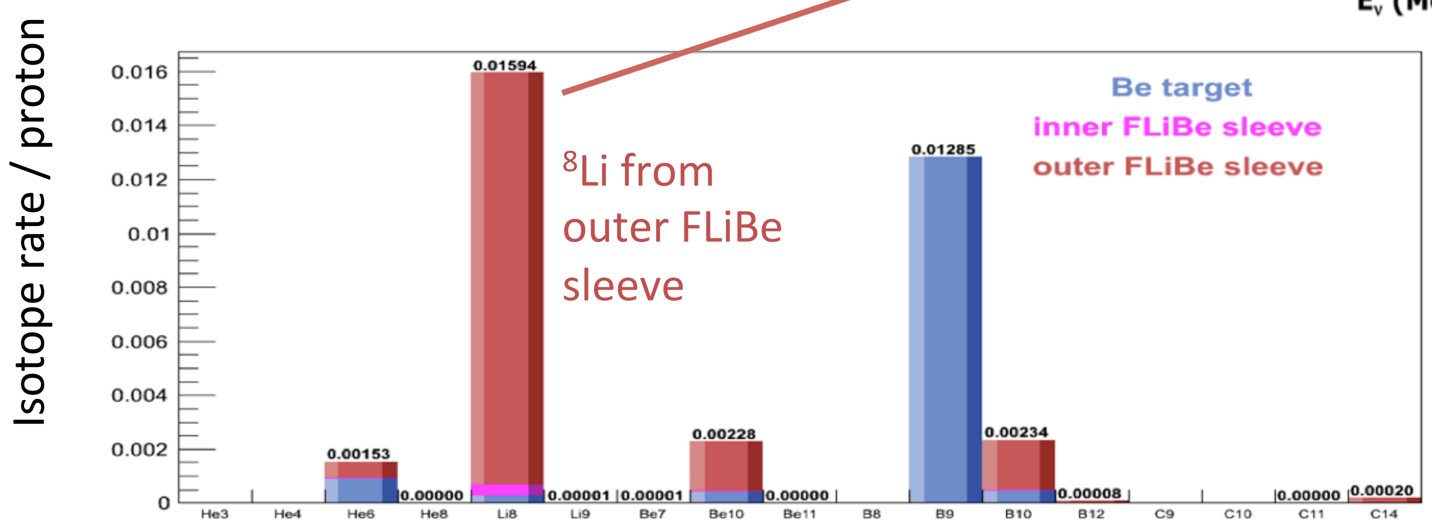
E_{max}	60 MeV/amu
E_{inj}	35 keV/amu
R_{ext}	1.99 m
R_{inj}	55 mm
$< B >$ @ R_{ext}	1.16 T
$< B >$ @ R_{inj}	0.97 T
Sectors	4
Hill width	28 - 40 deg
Valley gap	1800 mm
Pole gap	100 mm
Outer Diameter	6.2 m
Full height	2.7 m

Cavities	4
Cavity type	$\lambda/2$, double gap
Harmonic	4th
rf frequency	32.8 MHz
Acc. Voltage	70 - 240 kV
Power/cavity	310 kW
ΔE/turn	1.3 MeV
Turns	95
ΔR /turn @ R_{ext}	> 14 mm
ΔR/turn @ R_{inj}	> 56 mm
Coil size	200x250 mm^2
Current density	3.1 A/mm^2
Iron weight	450 tons
Vacuum	$< 10^{-7}$ mbar

High-intensity, well-understood $\bar{\nu}_e$ beam

- IsoDAR $\bar{\nu}_e$ beam
  - About 0.016 ^{8}Li isotopes per proton produced
    - Giving a very high-intensity $\bar{\nu}_e$ flux
  - ^{8}Li is the only significant neutrino producing isotope
    - Well-understood energy spectrum
  - ^{8}Li production mainly from neutron capture on FLiBe ^{7}Li sleeve

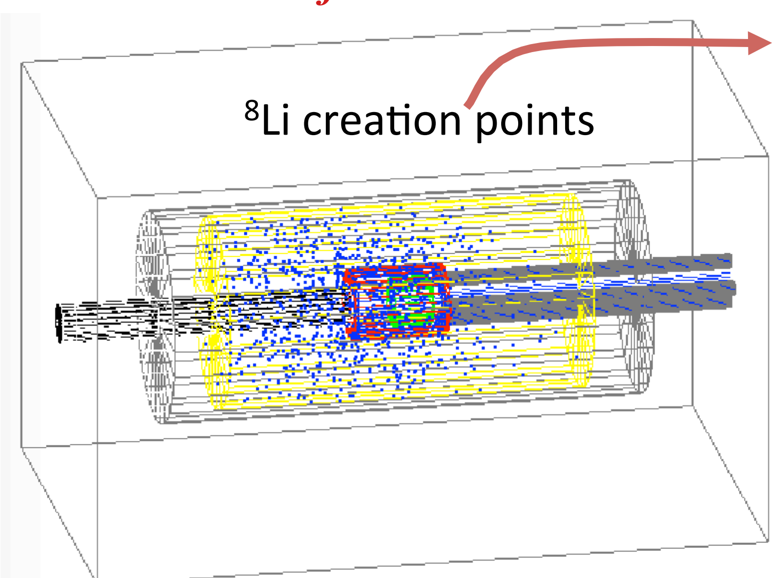


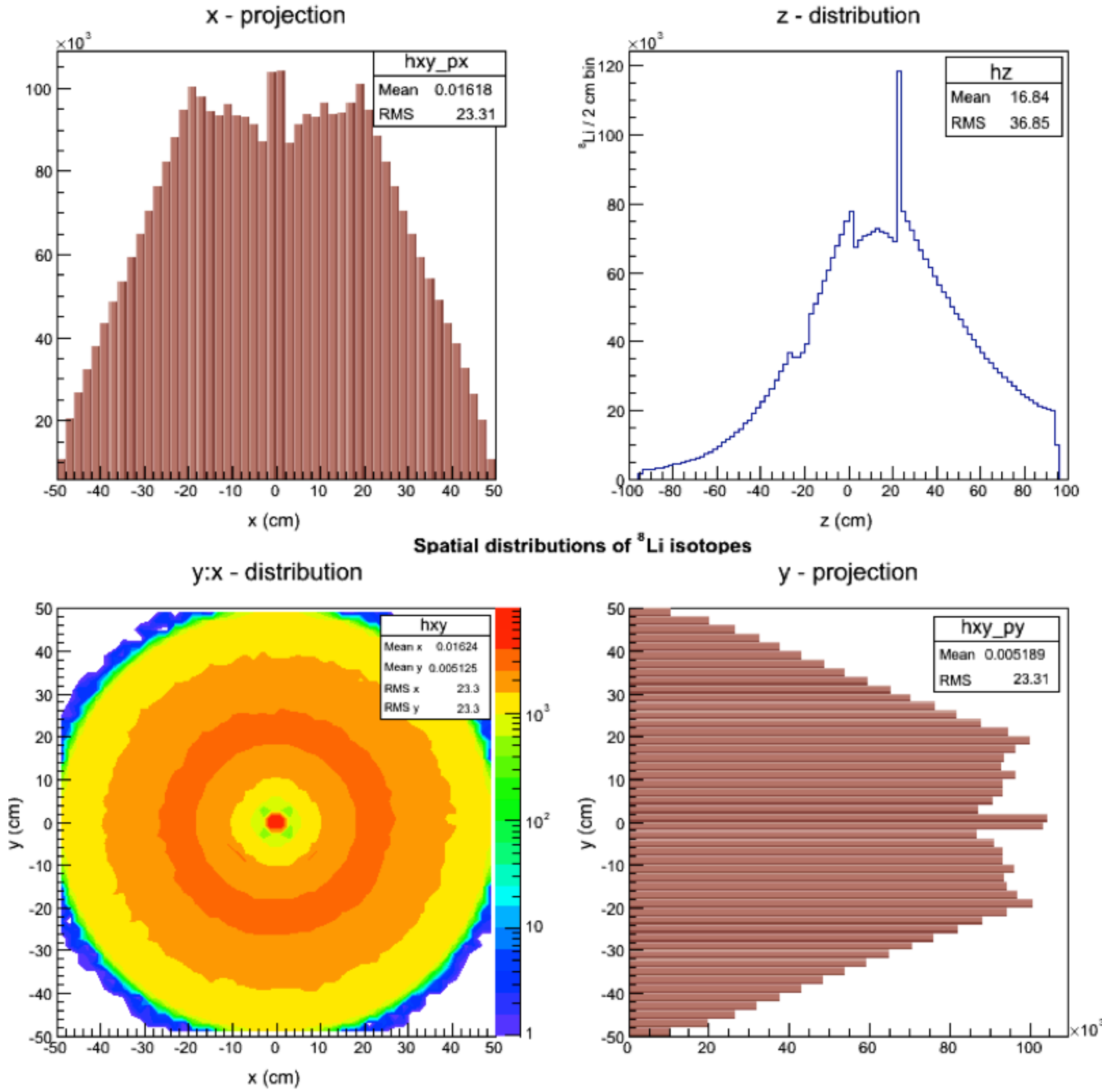


Compact neutrino source plus KamLANDs good L, E resolution

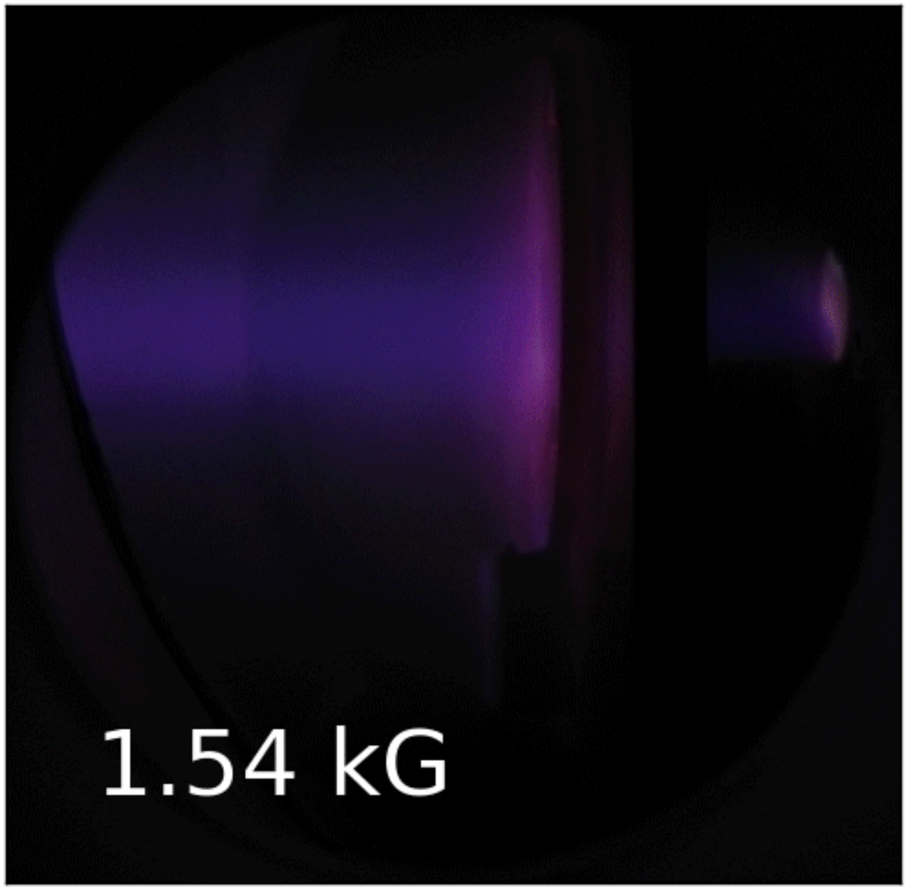
- IsoDAR produces compact neutrino source:
  - $\sigma_x = \sigma_y = 23$ cm and $\sigma_z = 37$ cm
  - Well-understood energy spectrum
- KamLAND has excellent resolution
  - vertex: $12\text{cm}/\sqrt{E(\text{MeV})}$
  - energy: $6.4\%/\sqrt{E(\text{MeV})}$

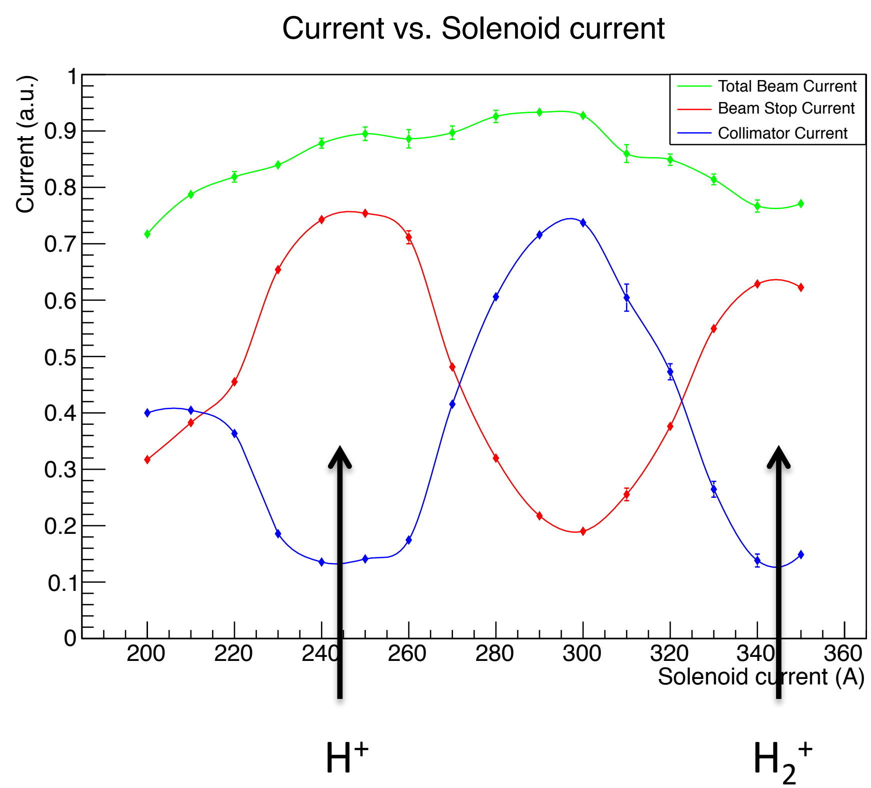
⇒ These combine to give excellent L/E resolution for oscillation studies

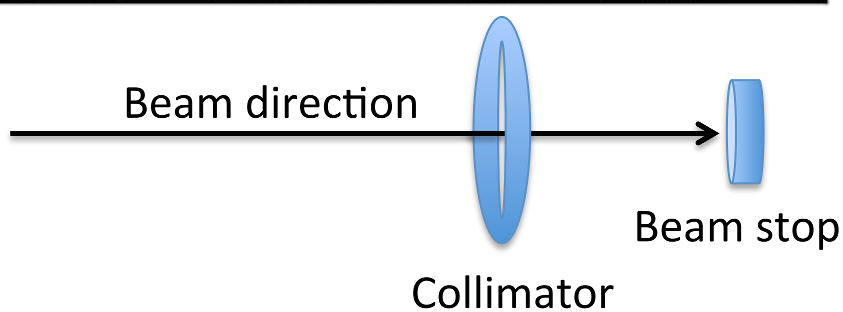




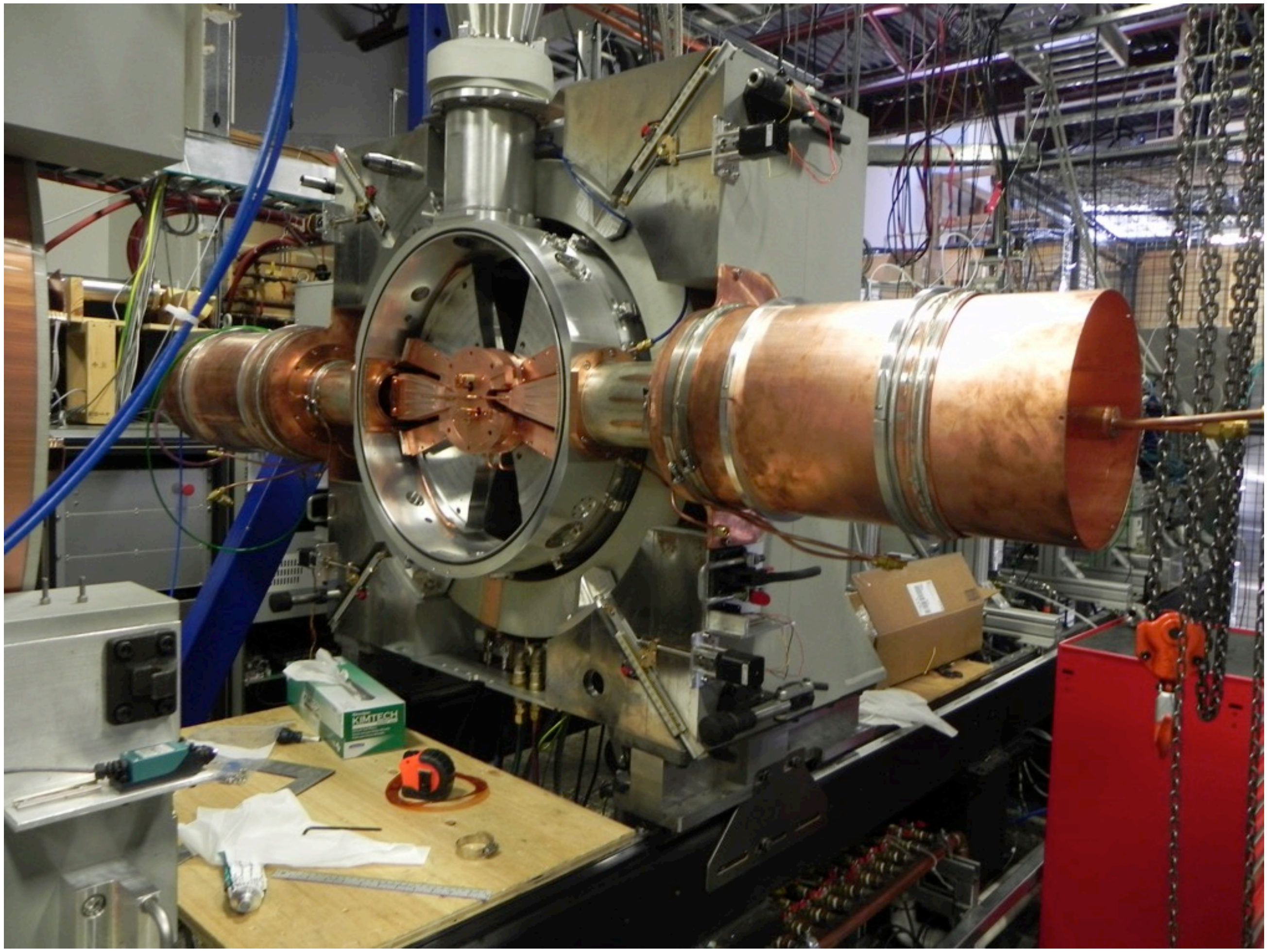
Commissioning the Ion Source



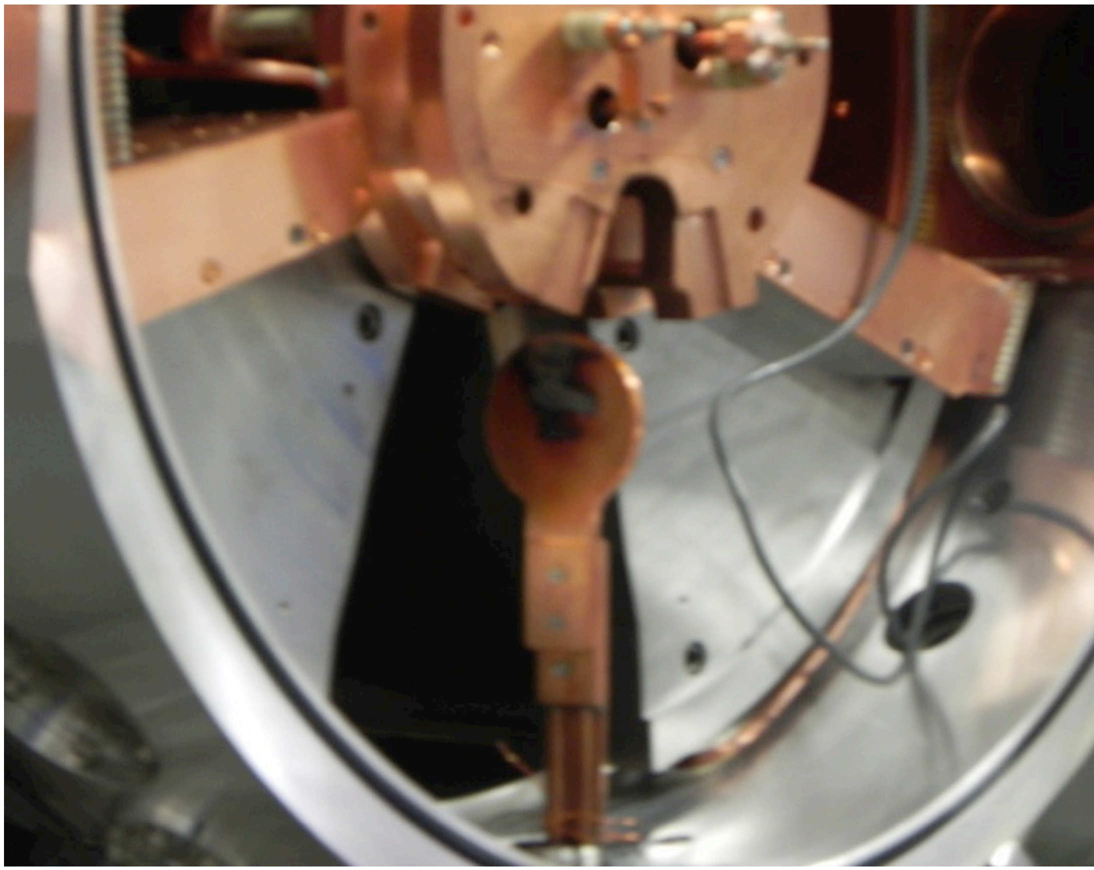


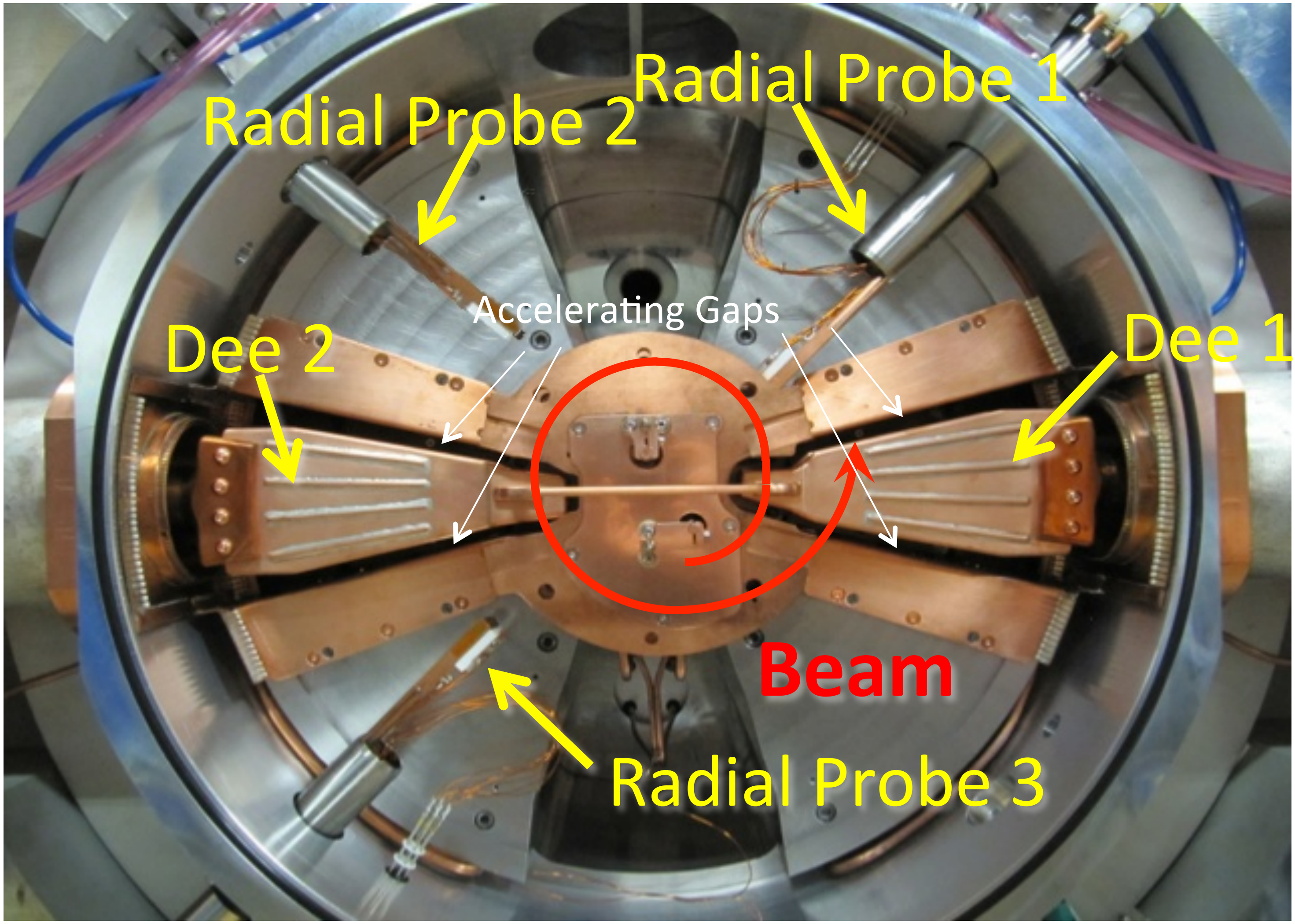


1 MeV Test Cyclotron at BEST, Inc



First Beam Through Inflector





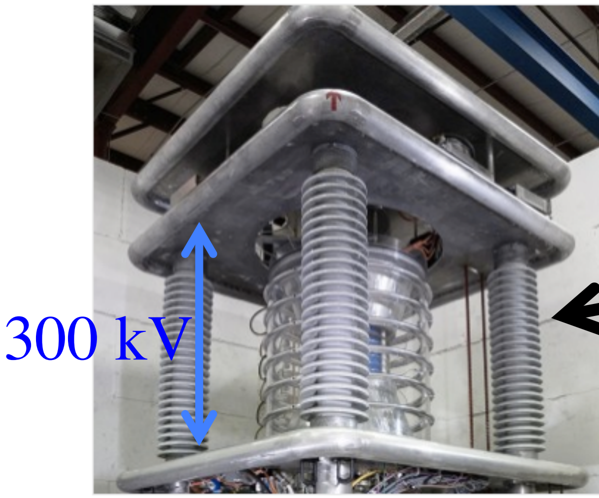
Beam injected and accelerated in test cyclotron 3.5 turns (600 keV)!

Recently raised: Why not a next-generation D-T generator?

PHOENIX NUCLEAR LABS

PRODUCTS TECHNOLOGY SOLUTIONS CASE STUDIES CAPABILITIES A

High Yield Neutron Generator



PNL's High Yield Neutron Generator is the highest-yield deuterium-deuterium (DD) compact neutron generator in the world. We have measured greater than $3{\times}10^{11}$ DD n/s, and products are available with variable neutron output between $1{\times}10^{11}$ and $5{\times}10^{11}$ n/s. Because the system uses no tritium, regulatory burden and required shielding are significantly reduced. The generator utilizes a gaseous deuterium target to maximize neutron yield and system lifetime. Because the High Yield Neutron Generator does not utilize a solid target, the system lifetime is measured in years rather than hours. For customers that need even higher neutron yield, the system can be quickly reconfigured to operate with tritium if the appropriate licenses and shielding are in place. With tritium fuel, this generator will yield $1{\times}10^{13}$ to $5{\times}10^{13}$ DT n/s.

Expected date for D-T: 2016

Produces fewer n/s:
10^{13} n/s vs IsoDAR 10^{15} n/s
But cheaper and needs less power.

Generator w/ HV cage is very large, and neutrons are isotropic.
How do you surround w/ sleeve?

How do you maintain/service this device if it is integral to the sleeve?

How do you assure a very pure ^{8}Li flux with so much internal material?

Engineering + physics issues → prefer the cyclotron solution

Cost-effective Design Options for IsoDAR

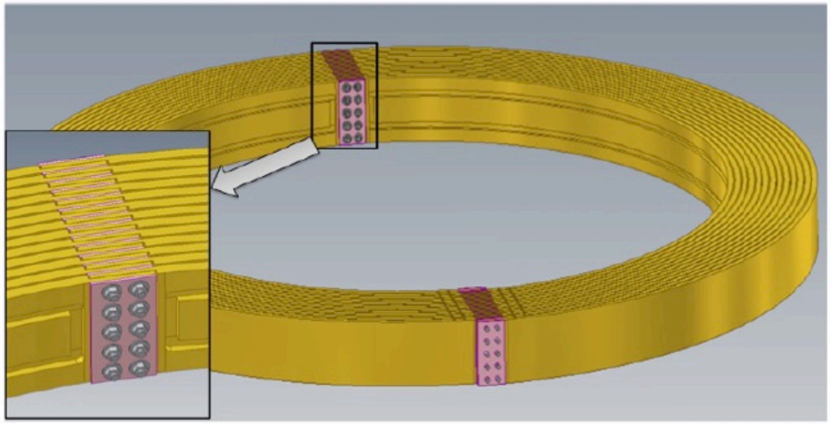
arxiv: 1210.4454

Are cyclotrons really the best option for isotope decay-at-rest?

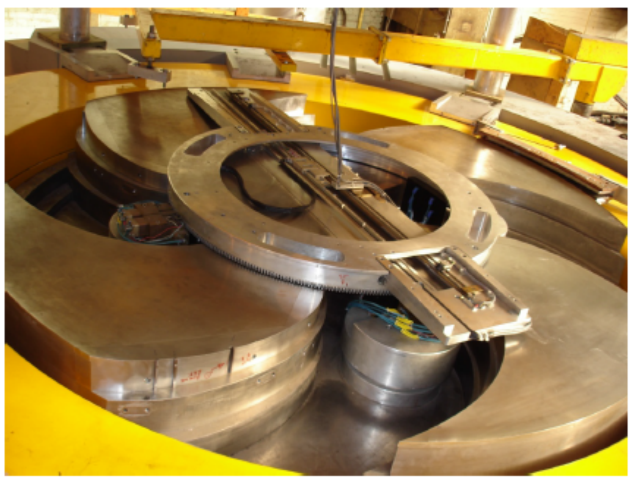
Assessment

- Good
- Moderate
- Bad

	IsoDAR Base Design	RFQ/Separated Sector Cyclotron	LINAC, 30 MeV, 40 mA	Modified Beta Beam Design	New Detector at Existing Beam
1. Cost	Good	Moderate	Bad	Moderate	Bad
2. $\overline{\nu}_e$ rate	Good	Good	Good	Bad	Good
3. Backgrounds low	Good	Good	Good	Good	Moderate
4. Technical risk	Moderate	Moderate	Moderate	Moderate	Good
5. Compactness	Good	Moderate	Bad	Good	Moderate
6. Simplicity underground	Good	Moderate	Moderate	Bad	Moderate
7. Reliability	Good	Good	Good	Bad	Good
8. Value to other experiments	Good	Good	Good	Bad	Bad
9. Value to Industry	Good	Moderate	Moderate	Bad	Bad



From the IBA report…



Mapping system installed inside the magnet

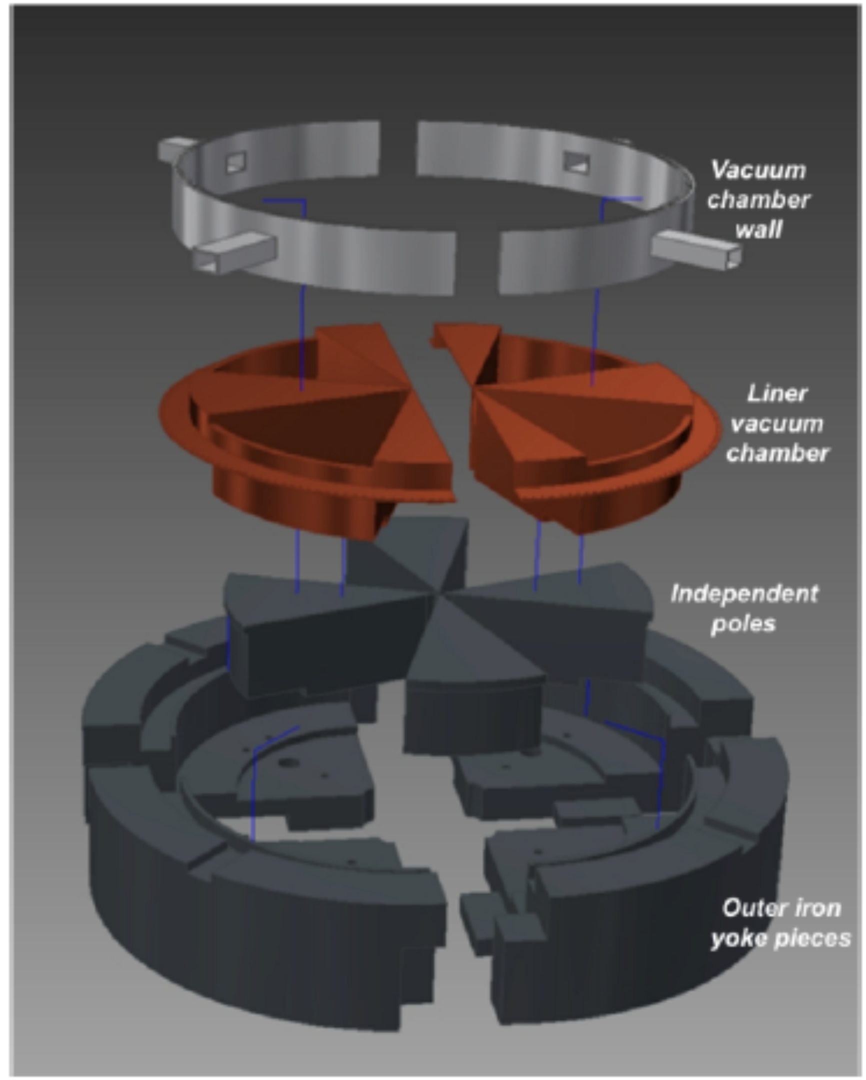


Figure 3 – Cyclotron general split parts